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No. 611

THE SONIC ALTIMETER FOR AIRCRAFT

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Washington  
August 1937

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PART I

HISTORY AND PRESENT STATUS OF THE SONIC ALTIMETER

With

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MODERN FLIGHT CONDITIONS

ABSTRACT

The general object of this report is to discuss the results already achieved with sonic altimeters in the light of the theoretical possibilities of such instruments. From the information gained in this investigation, a procedure is outlined to determine whether or not a further development program is justified by the value of the sonic altimeter as an aircraft instrument.

The information available in the literature is reviewed and condensed into a summary of sonic altimeter developments which is presented as the last page of this report. The instruments of Behm, Rice, Florisson, Dubois and Laboureur, Nandillon, Jacquet and Badin, Delsasso, and the Electroacoustic Co. are described both in principle and mechanical detail. The general requirements for the source of sound and the receiving system of a sonic altimeter are outlined. Evolution of the sound source is traced from the pistol sender of Behm to the mechanically excited diaphragm of Delsasso, the electrically driven diaphragms of Nandillon and Jacquet-Badin, the air-blown whistles of Rice and Florisson and finally, the air-operated sirens of Dubois-Laboureur and the Electroacoustic Co. Various methods of receiving the echo and timing the interval between the signal and the echo are considered, starting with auditory reception and visual observation of a rotating hand as used in the first instruments and ending with the completely automatic electrical microphone-chronoscope systems.

The operating ranges and weights of the sonic altimeters are noted and a "figure of merit" is derived for each instrument based on the ratio of maximum useful altitude under airplane cruising conditions to the installation weight.

A theoretical discussion is given of sonic altimeter errors due to uncertainties in timing, variations in sound velocity, aircraft speed, location of the sending and receiving units and inclinations of the flight path with respect to the ground surface. Plots are included which summarize the results in each case. An analysis is given of the effect of an inclined flight path on the frequency of the echo.

A brief study of the acoustical phases of the sonic altimeter problem is carried through. The results of this analysis are used to predict approximately the maximum operating altitudes of a reasonably designed sonic altimeter under very good and very bad conditions. A table is given of these limiting altitudes for various amounts of sound power in the signal. Losses due to high sound intensities, absorption in the atmosphere, turbulence effects and reflection at the ground are discussed. The physical limitations of the sound source with regard to output, directivity and pulse length are considered. It is shown that no limitation is placed on the performance of a modern sonic altimeter by either the chronoscope or the receiving microphone. Ruggedness, freedom from vibration, and selectivity effects are the important properties of the receiver rather than high sensitivity. In general, the design factors limiting the maximum operating altitude of a sonic altimeter are: 1) the residual sound intensity due to the aircraft which is not eliminated by the filter system of the receiver, and 2) the sound power output of the source which is effectively directed toward the receiver along the echo path. The necessity for directive horns in both the sending and receiving systems is discussed with special reference to future possibilities. Some properties of filters are considered and the possibility of using combinations of acoustical, mechanical, and electrical units is noted.

A final comparison is made between the estimated and experimental maximum operating altitudes which shows a good agreement where quantitative information is available. It is noted that the best possibility for improving sonic altimeter performance is to reduce the absolute

value of the echo intensity required to operate the receiver. It is shown that this can probably be accomplished by a survey of the aircraft noise which exists in particular cases and the design of properly selective filter systems.

#### ACKNOWLEDGMENT

The writer wishes to acknowledge the assistance received from Dr. R. H. Boden and Mr. George Van Schliestett in the general preparation of this report. Mr. Vincent Salmon, Professor W. T. Hall, and Dr. John Trimmer have helped by collecting and examining the references used for discussion of the acoustical aspects of the sonic altimeter problem.

#### INTRODUCTION

Aircraft must fly near the ground for a considerable period in connection with each take-off and landing. For safety in these operations the pilot must have an accurate and continuous knowledge of his altitude above the ground level. Under ordinary conditions, visual judgments of distance by a skilled operator automatically take care of this problem. However, when visual observations are impossible due to darkness, fog, or a heavy storm, some instrument for measuring height above the ground is necessary. Barometric altimeters can be used for this purpose only if the existing barometric pressure and the local elevation of the ground above sea level are known. The ordinary barometric altimeter whose hand makes one revolution for 10,000 feet altitude is not sufficiently sensitive for safe landing operations under any circumstances. This state of affairs has produced many devices designed to measure absolute altitude without an external visual reference. General discussions of the problem have been given by Lubcko (references 3 and 4), L6gliso (reference 11), Florisson (reference 16), Rice (reference 13), and Dubois and Labourbur (reference 19). The ideas proposed generally depend upon the reflection of either electromagnetic or sound waves from the ground surface. A number of investigators have been able to produce working instruments using sound waves but there is no record of similar successes with any other scheme. The sonic altimeter has three essential parts: (1) an emitter which sends out a brief sound signal at controlled

intervals; (2) a receiver which detects the echo of the signal when it returns from the earth; and (3) a chronoscope which measures the time interval between signal and echo. Since the velocity of sound in air is substantially constant, the chronoscope is ordinarily calibrated directly in altitude for some average set of conditions.

Sonic altimeter experiments were started in Germany before 1925 by Alexander Behm (references 6 and 7). Rice in the United States (reference 14) and Florisson in France (reference 16) had also attacked the problem before 1930. In each case promising results were achieved and an instrument suitable for service tests was produced.

Interest in sonic altimeters slackened considerably when the sensitive altimeter manufactured by the Kollsman Instrument Company (reference 10) came into general use soon after 1930. This instrument uses the barometric principle and has sufficient precision for blind landings if the barometric pressure at the ground is accurately known. Radio communication insures that all the required information is at the pilot's disposal so long as he operates from properly equipped airports. However, the radio and sensitive altimeter combination does not take care of a pilot who must "push down through" heavy clouds in search of a low ceiling without an exact knowledge of his position. There are also instances when radio communication fails or it is desirable to fly by "contact" under a very low ceiling. With such conditions, irregular hills combined with fog which actually reaches the ground in some places are very dangerous. Even with good visibility smooth water surfaces often make accurate judgments of height difficult at low altitudes. In all these cases an instrument to indicate actual height above the ground for altitudes less than 1,000 feet would be useful. It is certain that a sonic altimeter with units already developed can be made to meet this requirement. In the present state of the art, the equipment would be relatively heavy and cumbersome. A satisfactory installation could be made to fit easily into a modern transport plane with a total weight under 75 pounds. Since this weight represents fuel for less than 15 minutes flying in a large airplane, the value of this much flying time must be balanced against the advantage of an indicator giving actual altitude above the ground. The instrument would not only serve as insurance in extraordinary situations, but would almost certainly be used by pilots to improve the precision of landing and take-off operations. Finally, there is the possibility of

using the sonic altimeter as an auxiliary control for blind landings to establish automatically the proper relation between the attitude of an airplane and its height above the ground.

Obviously, the fate of the sonic altimeter must depend upon results from extended tests under service conditions. Before such a project is undertaken, the previous work on sonic altimeters should be studied to insure that the best type of equipment is used for the tests. The present report presents such an examination of the material already available on sonic altimeters with special reference to the results obtainable from commercial instruments. These results are compared with performance limits estimated from a study of the physical principles involved. Recommendations for a program of sonic altimeter research are based on the conclusions drawn from this investigation.

### GENERAL REQUIREMENTS

Figure 1 shows the essential geometrical features of the sonic altimeter problem. An emitter S sends out a sound signal which strikes the ground and is picked up by a receiver at R. The apparatus is completed by a chronoscope for measuring the time interval between the signal and the echo which is a function of the airplane speed, the speed of sound and the altitude. Individual instruments differ only in the means used for carrying out these three functions. Fortunately the speed of sound is almost constant and the airplane speed has a small effect under ordinary conditions, so the echo time is almost proportional to altitude. The errors due to various geometrical factors are considered in a later section.

The practical requirements for sonic determinations of altitude are:

1. The source of sound must be powerful enough to produce an echo at the airplane which is more intense than the aircraft noise in the same frequency range. This condition is difficult to fulfill at high altitude due to absorption, reflection and spreading losses over the echo path.

2. The receiving system must be sufficiently sensitive and selective to detect the echo in the presence of high intensity noise from the aircraft and give a positive indication on the chronoscope.
3. The sound source must be such that the start of the time interval between the signal and the echo is sharply defined.
4. The chronoscope for measuring this echo time must be capable of accurately measuring time intervals required by the operating range of the altimeter. An altitude of one foot corresponds to about  $1/600$  of a second and 1,200 feet to about 2 seconds.

In general, the lower limit of the operating range is determined by the ability of the apparatus to produce and measure sharply defined short echo times while the upper limit depends upon the power of the source to produce usable echos at the airplane. A study of each phase of the general sounding process is given in a later section.

#### DEVELOPMENT OF THE SONIC ALTIMETER

After the TITANIC disaster in 1912, due to collision with an iceberg, several investigators started research on the use of sound waves for the location of objects under bad visibility conditions. This work soon produced the marine depth finder as a byproduct. Alexander Behm (references 1, 2, 3, 4, 5) of Germany developed his ECHOLOT which later became known as the BEHMLOT. In the United States, R. A. Fessenden of the Submarine Signal Company (references 1, 2, 3, 4) worked out the FATHOMETER. C. Florisson (references 11, 16, 17) of France also made contributions to the problem, especially in the use of supersonic frequencies. The later art of sonic altimetry owes a definite debt to each of these marine developments.

Behm (references 5, 6, 7, 8, 9, 10, 11, 12) adapted his marine ECHOLOT to aerial soundings from airships. His experiments in 1925 on the Zeppelin Z.R. III are reported as successful up to 200 meters altitude. Working with the Deutschen Versuchsanstalt für Luftfahrt in the same year, Behm applied his instrument to an airplane. Figure 2

shows the essential parts of this apparatus. A pistol firing blank cartridges served as the source of sound, while echos were received by carbon powder microphones and carried to earphones. Altitudes were estimated by an observer wearing the earphones and noting the positions of a moving hand on a scale when the signal and its echo occurred. This so-called method of visual-acoustic coincidence required close attention by the observer and gave inaccurate results at low altitudes. An adaption of the optical chronoscope used in the marine ECHOLOT improved this situation by making the observation of altitude an entirely visual process of good precision. Details of the Behn apparatus are discussed in Appendix A.

An experimental airplane study of the BEHMLOT by Schreiber (reference 9) carried out in 1930 showed a mean error of  $\pm 3.5$  meters in altitude readings up to a maximum of 100 meters. Behn's work brought out clearly the difficulty of detecting the signal echo in the presence of intense "parasite" flight noises from the airplane and its power plant. No attempt was made to increase the ratio of echo intensity to parasite noise intensity by the use of either acoustic or electrical filters. In the earlier forms, the BEHMLOT required manual operation of the sound source. Even after this handicap was overcome by using an automatic pistol, the difficulty of carrying a large supply of ammunition remained.

Rice (references 4, 10, 11, 13, 14, 15) and Florisson (references 4, 11, 16, 17, 18) worked on the sonic altimeter problem independently during the years 1929-1932 and produced similar instruments with approximately the same performance. In addition to his contributions to the general scheme, Rice made especially valuable studies of sound sources for the sonic altimeter. The results of this work led to the adoption of a whistle blown by compressed gas for his instrument. Florisson was particularly interested in acoustic disturbances due to the air stream flowing across openings in emitters and receivers. He found that these difficulties could be eliminated by mounting the acoustic units with their openings flush in the surface and using a thin sound permeable covering to preserve the aerodynamic form.

The instruments of Rice and Florisson differed from those of Behn in the use of a pure tone signal. With the sound energy concentrated in a single selected frequency instead of a wide band as in the case of a shot, it became

possible to use resonance effects in the receiver for increasing sensitivity and reducing interference from airplane noises. The actual sensitive element for reception of the echo was the human ear. Altitudes were estimated by an observer listening for the echo and watching the moving hand of a chronoscope.

Figure 3 shows the essential elements of the Florisson system. Compressed air is supplied to a chamber C and escapes through the whistle S when an electrically controlled valve is opened. This whistle is mounted at the focus of a reflector set flush with the surface of the airplane and covered with sound permeable material. The echo is received by a reflector R with an open tube placed at the focus. This sound tube is connected to earpieces worn by the observer. An acoustic filter F is placed in the sound tube T in addition to the electrically operated valve for closing the line during the signal. Timing control is taken from a constant-speed motor with its armature shaft placed along the axis A-A. A pointer I is attached to the shaft and moves over a scale graduated in altitude. A cam 4 with an indentation 3 is also carried by the motor shaft. The cam follower 2 is so placed that the contacts 1 are closed for a short time interval as the pointer passes through zero of the scale. When the control circuit has been closed by a manually operated switch, each passage of the pointer through zero will be accompanied by a blast of the whistle and a short blocking of the sound tube by the control valve to reduce the intensity of the direct signal. Florisson introduced an auxiliary pointer i, adjustable by the observer, to serve as a reference in fixing the pointer position at the time of the echo. A second dial and pointer i' are shown by figure 3 to show the possibility of multiple indicating units.

Florisson also suggested two other systems for time measurements which are described in Appendix A. One system reduces the time measurement problem to a judgment of the coincidence of two sounds while the other uses an optical system and an oscillograph to produce entirely visual indications. However, the system actually reduced to commercial practice by Florisson (reference 17), used the arrangement described in figure 3. This instrument is available from the Société de Condensation et d'Applications Mécaniques of Paris.

The problem of the proper signal frequency and dura-

tion was prominent in the work of both Rice and Florisson. It was recognized that the human ear is an excellent detector for sounding echos of the proper frequency, not only on account of its sensitivity but also because a trained observer is able to recognize a characteristic echo against a bad background of extraneous noise. On the other hand, the accuracy of time-interval measurements by even a skilled observer with his entire attention on the problem is too low for good soundings at small altitudes. However, it was found that direct judgment of distance from the time interval between the signal and the echo could be used by a trained observer.

Rice carried out an analysis which caused him to use a frequency of 3,000 cycles per second with a signal duration of  $1/100$  to  $1/50$  of a second. The reasons for his choice are listed below:

- "....1. Many cycles available in a short blast.
2. Reduced masking effect from low frequency noise.
3. Relatively low scattering effects.
4. Best ear sensitivity.
5. Wide separation between engine and signal frequencies permit effective filtering or tuning.
6. Directive transmitters and receivers of moderate size...."

An extended series of flight tests gave the following results for the Rice-G.E. sonic altimeter.

- "....1. With engine running at cruising speed, reliable echos were obtained at 800 feet and below.
2. With engine throttled for gliding flight, reliable echos were obtained at 1,600 feet and below.
3. The echo was lost at 800 feet when bank or climb angle reached approximately  $30^{\circ}$  degrees.

4. Echos at 800 feet were clearer and sharper over flat ground, water and ice than over trees and fields.
5. When flying over mountainous country, the rise and fall of the ground was easily detected by the change in the time interval between outgoing and received signal, as measured by the pointer on the altitude indicator or as judged by the ear alone.
6. When flying parallel to a steep hillside, the echo was noticeably long and drawn-out by reflection from varying distances.
7. When coming into a landing, the approach of the ground was very evident due to the closing-in of the time interval between signal and echo, and when the plane reached approximately 5 or 10 feet from the ground, the outgoing signal and the echo blended into a continuous reverberation. This provided a definite notification point which the pilot could use for successful blind landings...."

Rice gave no definite information on the effect of weather conditions.

In addition to the airplane experiments, Léglise noted (reference 11) that a G. E. sonic altimeter installed on the airship "Los Angeles" gave soundings up to 900 meters over the ocean. This difference in range was, of course, largely due to the reduced parasite noises on an airship.

Florisson did not give the frequency used for his whistle but noted that the signal had a duration of about 0.03 second. His apparatus gave soundings up to about 150 meters under cruising conditions and about 300 meters with engines throttled. The readings could be carried down to 5 or 10 meters from the ground.

The weight of Rice's first installation was 45 pounds, which was later reduced to about 30 pounds. Florisson's outfit had approximately this same weight. However, Rice used one of the engine cylinders as his source of power while Florisson allowed over 10 pounds for a compressor and its accessories. No quantitative data are available

on the relative sound-output power of the two instruments but it appears that if Rice had used a separate compressor, the maximum range per unit weight would have been almost the same in the two cases. It is also remarkable that both investigators found that the difference in airplane noise effects between cruising and gliding doubled the useful range.

The work just described certainly demonstrates that sonic measurements between approximate altitudes of 10 and 1,000 feet can be carried out in practice. Two disadvantages are immediately apparent: (1) the apparatus is relatively heavy and (2) reliable results require constant attention from a trained observer. This first characteristic effectively prevents the use of such equipment on small airplanes but becomes a less important objection on large transports. The second difficulty is more serious and must certainly be overcome before sonic altimeters can be generally accepted as a routine flight instrument although in a large airplane the radio operator or the co-pilot could be assigned the duty of making soundings. This altitude information could be placed before the pilot by an arrangement similar to that already suggested by Florisson.

Raymond Dubois, of Constructions Electro-Mécaniques d'Asnières, and Commandant Laboureur started research on the sonic altimeter problem in 1931 and continued work until at present their instrument is available commercially (references 4, 11, 18, 19, 20, 21, 22, 23, 24). Dubois and Laboureur directed their efforts particularly toward an automatic visual indicator and a source of sound to produce a very short signal. They pointed out that any sound depending upon resonant frequency vibrations requires several cycles to reach maximum intensity and then decays over a number of cycles depending upon the particular system. Since any receiving system requires some minimum intensity for a detectable excitation, there will always be a time interval between the arrival of the first echo cycle and an indication by the receiver. This time interval will vary with the echo intensity until at the upper limiting altitude the indication will occur only when the strongest cycle of the echo is reached. With specular reflection at the ground this error in timing will correspond to 5 or 6 cycles of the signal when a whistle is used.

An extended investigation of whistles, vibrating membranes, and sirens as sound sources led Dubois and

Laboureur to adopt the air-blown siren for their sonic altimeter. They found that the siren used a relatively small amount of compressed air and that the sound reached its full amplitude on the second oscillation. By the use of a quick-acting balanced valve it was possible to produce a signal duration of 0.01 of a second. Such a short signal gave no advantage with the ear as the receiving element since an observer was unable to distinguish between a short sound of given intensity and a sound twice as long but half the intensity. On the other hand, a short, sharply defined siren signal worked better with automatic receivers than sounds from a whistle. The frequency used was 1,500 cycles per second.

For the sensitive element of the receiver Dubois and Laboureur used an electromagnetic microphone with the diaphragm tuned to a frequency slightly different from the signal frequency. With this design the unit responded well to the signal while any random shocks or noises excited the diaphragm at its own natural frequency and the effect of such disturbances on the indicator could be reduced by an electrical band-pass filter in the amplifier.

In the chronoscope Dubois and Laboureur replaced the previously used mechanical and optical arrangements by an entirely electrical system. Altitude readings were indicated directly on a calibrated dial by a nonrotating pointer. This result was obtained by use of a neon discharge tube to control the current flowing into a fixed condenser. A steady potential between the breakdown and extinction voltages was applied to this tube. A pulse of voltage at the instant of the signal started the tube and a second pulse from the microphone stopped the tube when the echo was received. During this time interval the condenser was charged through a resistor and a vacuum tube used as a rectifier. With this arrangement the voltage across the condenser terminals was a function of the echo time. After the neon tube was extinguished the vacuum tube and a meter in the plate circuit acted as an electromotor to indicate the condenser voltage. The reading of this meter remained constant until it was necessary to discharge the condenser for a new sounding when the pointer returned suddenly to the zero altitude position. This type of indication was definitely better than that of the chronoscopes previously used but the instrument was still unsatisfactory on account of the "jump" back to zero between soundings. Dubois and Laboureur later remedied this difficulty by using a second condenser and vacuum tube

electrometer to give the indications. This second condenser was momentarily connected across the terminals of the chronoscope condenser just before its discharge for a new sounding. In this way the voltage of the second condenser, which was very small compared to the chronoscope condenser, always corresponded to the altitude of the last sounding and the change in position of the pointer between soundings was only the small shift corresponding to the actual variation in altitude. A more detailed description of the Dubois-Laboureur sonic altimeter is given in Appendix A.

A Dubois-Laboureur sonic altimeter was given flight tests in 1932 on several airplanes and in a nonrigid airship. Under cruising conditions over water, soundings were possible in an airplane up to 300 meters and practically continuous up to 250 meters. In the airship no limit was determined but it was probably about 500 meters. Over flat country of all kinds the range for level flight was about the same as over water. Under the worst conditions of weather and ground the apparatus always worked below 50 meters and gave usable results at 100 to 150 meters. It was found that the occasional echos received even at higher altitudes gave enough information for purposes of safety.

The weight of a complete Dubois-Laboureur installation was about 50 pounds, which gave their instrument about the same performance in terms of range per unit weight as the sonic altimeters already described.

The electrical chronoscope is certainly a worthwhile contribution to the art and can be made to give accurate and reliable results if properly installed and maintained. However, the scheme depends upon the use of a vacuum tube in a circuit of the "direct current" amplifier type and will be sensitive to changes in supply voltage and aging of the tube itself, aside from the necessity of recalibration if a new tube is installed. In case such a circuit is used for field service some simple arrangement for calibration should certainly be included in the installation. In this connection, it is interesting to note that the CEMA sonic altimeter, which is built under Dubois-Laboureur patents, uses an electromechanical indicator instead of the type described above.

Nandillon (references 11, 17) used an electrically driven diaphragm to produce the signal for acoustic sound-

ings. His receiver was an electromagnetic microphone which operated an indicator of the optical oscillograph type. Details of the units are given in Appendix A.

A completely electrical system had many advantages in the elimination of mechanical accessories and the possibility of using power directly from the aircraft supply. However, the output available from a single unit was too low for soundings except at low altitudes. Nandillon attempted to overcome this difficulty by using multiple element loudspeakers. In practice such an arrangement was both cumbersome and heavy. The photograph of figure 4 showing one of Nandillon's experimental installations illustrates this point. Nandillon's work was carried out as a secret investigation and no information on his experimental results is available.

Jacquet and Badin (references 4, 11, 18, 25) attacked the problem of making accurate soundings at very low altitudes. Their apparatus was completely electrical with the emitter and receiver combined into a single unit. Instead of the usual short signal and an interval timer as the indicator, they used a continuous signal with automatic modulation by the echo.

In this scheme the sound sent out by an electrical loudspeaker was continuous until the echo reached the receiver. When this occurred the signal was automatically cut off and the speaker remained silent until the end of the echo wave train reached the receiver, and then the loudspeaker immediately started again. This resulted in equally spaced intervals of signal and silence. The duration of these intervals was directly proportional to the altitude of the apparatus. Continuous indications were given by an electrical meter which measured the frequency of the automatic modulation. A brief description of the Jacquet-Badin instrument is given in Appendix A. This instrument had a weight of 9 kilograms. No actual test information is available but the scale graduations were carried to a maximum altitude of 50 meters. The inventors have definitely limited their efforts to an instrument for landing purposes.

The Jacquet-Badin sonic altimeter is interesting as illustrating a new attack on the indicator problem. However, an instrument with such a low operating range would be of little use for the important function of detecting the ground as an airplane descends from a high altitude.

In some cases a warning at 150 feet would be helpful but the situation would be much better if the warning occurred above 500 feet altitude.

L. P. Delsasso, working under a grant from the Guggenheim Fund for the Promotion of Aeronautics, investigated certain phases of the sonic-altimeter problem (references 4, 10, 26). His attention was particularly directed toward geometrical errors of the sonic altimeter due to aircraft speed, ground inclination, etc. He also analyzed the noise spectrum from aircraft and studied atmospheric effects on transmission of the signal.

Delsasso used a tuned diaphragm excited by a mechanical blow as the source of sound. His receiver was a diaphragm with an electrical contact pressed against the center of the diaphragm controlling an indicating circuit. The mechanical parts were so constructed that the receiver was insensitive to noises from the aircraft but a weak sound of the signal frequency caused an immediate break of the contact. A chronoscope of the type used in the FATHOMETER marine sounder was connected to the receiver. This instrument had a circular disk rotated at uniform speed inside a scale graduated directly in altitude. An automatic control system caused a signal to be released each time the neon tube passed the scale zero. A flash of the neon tube occurred when the echo caused a break of the receiver contacts and produced a voltage pulse in the output of a vacuum-tube amplifier. Altitude could be accurately determined from the position of the neon tube flash on the scale. Delsasso's apparatus is described in Appendix A.

Delsasso's sonic altimeter was installed on a Goodyear blimp and gave reliable results as high as 350 feet and as low as 4 feet. The weight of his apparatus is not given but this is of little importance since he made no attempt to produce a commercial instrument. In particular, his experiments showed the desirability of studying the effect of turbulence on sound transmission in the atmosphere.

Henry Hughes and Son have started development work on a sonic altimeter (references 30, 31). No engineering details are available for the apparatus, which is apparently still in the experimental stage.

Electroacoustic G.m.b.H. of Kiel, Germany, have developed a sonic altimeter called the ECHOSCOPE for commercial

purposes (references 27, 28). This instrument was used on the Hindenburg, and is to be installed on the new Zeppelin LZ 130.

The ECHOSCOPE uses a siren supplied through a reducing valve from a compressed-air reservoir as the source of sound. An electromagnetic microphone acts as the sensitive element in the receiving system and operates an electromechanical chronoscope through an amplifier. The chronoscope has a constant-speed motor which moves a pointer over the altitude scale. An electrical clutch system within the instrument starts the pointer from zero when the signal is sent out and stops the pointer when the echo reaches the receiver. The pointer is automatically returned to zero after each sounding and the cycle is repeated. Two scales are provided for maximum altitudes of 100 and 500 meters, respectively. In the lower range, soundings are repeated at 1.5-second intervals. This interval is increased to 7.5 seconds in the high range. The change from one scale to the other is made by a manual-control knob. Further details of the equipment are given in Appendix A.

The ECHOSCOPE gives soundings under normal conditions up to 600 to 1,000 feet with automatic indications. Above this limit the echo becomes too weak to operate the indicator but soundings can be carried out to greater altitudes by using earphones plugged into an outlet in the amplifier. In this case the chronoscope hand rotates continuously and altitudes are observed by the method of visual-auditory coincidence.

An uncertainty of  $\pm 1$  foot is claimed for the ECHOSCOPE on the basis of a precision of  $1/600$  of a second for the chronoscope. No mention is made of the effect of the 0.01 of a second signal length on the sounding process. With the apparatus described, the uncertainty in altitude should be small but a value of  $\pm 1$  foot appears to be an optimistic estimate.

Including all air valves and one high-pressure storage cylinder but no wires or piping, the ECHOSCOPE weighs about 60 pounds. The air supply is sufficient for 200 to 250 soundings for the low range with the siren pressure at 4 atmospheres. On the high-range scale a working pressure of 8 atmospheres is used which reduces the number of soundings from one bottle to 125. These figures correspond to

6 minutes and 15 minutes of continuous operation on the low- and high-range scales, respectively. Such a short period of operation will limit the usefulness of the instrument for general purposes. This difficulty can be eliminated by the installation of a compressor to replenish the supply during flight.

Alexander Askenasy (reference 29) has applied for French patents on a sonic altimeter using automatic modulation of a continuous signal with indications from a frequency meter. He proposed to use a sound source driven from a vacuum-tube oscillator through a variable-gain amplifier. The gain of this amplifier was to be controlled by the output from a second amplifier connected to the receiver in such a manner that a strong echo produced a weak signal and vice versa. With this arrangement the signal could be automatically modulated to any desired extent and the modulation frequency used for operation of a frequency meter. Askenasy recognized the possibility of false modulation due to ground or atmospheric conditions and included an "automatic volume control" to keep the output of the receiving amplifier constant in spite of erratic variations in the echo intensity. He suggested that a meter to measure the amount of compensation required would serve to indicate the nature of the ground surface.

There is no record that an instrument of the Askenasy type was actually constructed. M. Jacquet in a review of Askenasy's patent pointed out that the automatic modulation scheme had already been used in the Jacquet-Badin sonic altimeter. Jacquet also showed that an actual instrument would require a modulation of 100 percent and in this case the automatic volume control would be useless.

#### PRESENT STATUS OF THE SONIC ALTIMETER

Plate I is a tabular summary of information on sonic altimeter developments as outlined in the previous section. Most of this work has been done during the last ten years, although Behm had made soundings from an airship before 1925.

On the basis of operating range, the Rice, Florisson, Dubois-Laboureur, and the ECHOSCOPE sonic altimeters have approximately the same performance, i.e., reliable operation up to an altitude of 500 to 1,000 feet under ordinary

cruising conditions. By this same criterion the instruments of Behn, Nandillon, Jacquet-Badin, and Delsasso are inferior to those already listed. The maximum working altitude can be considered as a rough measure of the effectiveness of the sound source. It follows that compressed-air whistles and sirens as used by Rice, Florisson, Dubois-Laboureur, and ECHOSCOPE are definitely superior to mechanically excited diaphragms, electrical loudspeakers, and pistols as used by the other investigators. With the exception of the pistol, all the sources have been designed to produce a signal of a constant frequency between 1,500 and 3,500 cycles per second. Frequencies in this range make enough cycles possible in a short blast to permit good selectivity in the receiver whether the human ear or a tuned microphone is the sensitive element. In addition, directive emitters, receiving horns, and filters of small size can be designed with good efficiencies.

The ear of a trained observer is the most sensitive and selective detecting element. Both Rice and Florisson used an observer as a necessary link in their systems while the ECHOSCOPE provides for auditory reception when the echos become too weak to operate the chronoscope directly. The inaccuracies introduced by a human being in measurements of short-time intervals with a rotating pointer chronoscope established a lower limit to reliable soundings at about 20 feet, which corresponds to  $1/30$  of a second. Below this, a trained observer can replace the chronoscope readings by his judgment of time intervals. In spite of the advantages of auditory reception, any sonic altimeter which requires more than a glance for the observer to obtain an accurate reading, is certainly unsatisfactory as an aircraft instrument.

The electromechanical chronoscopes of the BEHMLOT and the ECHOSCOPE, and the neon-tube chronoscope of Delsasso all give direct altitude information but require inspection for several seconds for a reliable reading on account of the intermittent nature of the indication. The same remark applies to chronoscopes using optical indications such as Nandillon's instrument and the early Behm units. The Dubois-Laboureur and Jacquet-Badin electrical chronoscope systems give steady indications but are apparently still in the experimental stage. The only instrument offered commercially which seems to have a continuously reading chronoscope is the CEMA sonic altimeter manufactured under Dubois-Laboureur and Bonscaren-Glazer patents. (See Appendix A.) No stress is placed on this point in

the CEMA pamphlet used as the source of information, but the description of the mechanism indicates that the only change in hand position between soundings would be that corresponding to the actual variation in altitude.

Weight data on experimental apparatus is liable to be deceptive since the instrument designs have seldom been refined and the allowance for fittings, tubes, wires, etc., will vary from one case to another. Some refinements dictated by experience will probably be in the direction of reduced weight so that the range of 30 to 60 pounds reported for the sonic altimeters which have given best results, should include any satisfactory instrument built in the present state of the art. The ratio of maximum operating altitude under average cruising conditions to total weight should give a reasonably good figure of merit for sonic altimeter performance. The second column from the right-hand side of Plate I is devoted to this ratio for various sonic altimeters. The values are approximate since there is no assurance that the performance estimates were made under comparable conditions. The Rice-General Electric Co. instrument has the highest recorded ratio with 48 feet altitude per pound of weight. The range information is taken from a General Electric Co. information pamphlet which does not clearly state whether the value of 1,200 feet was taken under cruising or gliding conditions, so this ratio may not be a true value. The corresponding weight of 25 to 30 pounds for an installation is for an improved form of the equipment described by Rice (reference 13), and is supplied with compressed gas from one of the engine cylinders. This gives the G. E. instrument a decided advantage when compared with sonic altimeters which include a special compressor. In addition, the receiving system uses no amplifier but carried the echo to an observer through a simple tube system which also gives a weight advantage but reduces the usefulness of the instrument as compared to a direct reading chronoscope system.

With the exception of the improved G. E. sonic altimeter, the figures of merit for the various instruments fall into two classes. The Florisson (SCAM), Dubois-Laboureur (CEMA), and original Rice sonic altimeters, and the ECHOSCOPE have figures of merit between 15 and 20 feet of altitude per pound of weight. As noted above, the values are approximate at best so this good agreement is probably fortuitous. The BEHMLOT and the Jacquet-Badin sonic altimeter have figures of merit of 9 and 8 feet of

altitude per pound of weight, respectively, which shows that these are less effective than the instruments first mentioned. At present the most refined instruments are of European origin.

#### FUTURE POSITION OF THE SONIC ALTIMETER AS AN AIRCRAFT INSTRUMENT

The last section showed that several sonic altimeters are well beyond the experimental stages. At present, the most refined designs are of European origin with four manufacturers offering instruments for commercial use. These companies are:

- (1) Behm-Echolot-Fabrik of Kiel, Germany.
- (2) Electroacoustic of Kiel, Germany.
- (3) Constructions Électro-Mécaniques d'Asnières of Asnières, France.
- (4) Société de Condensation et d'Applications Mécaniques of Paris, France.

In the United States, only the General Electric Company of Schenectady, New York, has announced the construction of a sonic altimeter.

With the best of the instruments now available, reliable readings up to a limit between 500 and 1,000 feet can be expected under airplane cruising conditions. The weight of a complete installation including an air compressor will probably be between 50 and 75 pounds. Undoubtedly the range can be increased and the weight reduced by improvements based on experience, but it is certain that the sonic altimeter will remain a heavy instrument which will only operate at low altitudes.

When Rice started his sonic altimeter development in 1929, the blind-landing problem was receiving much attention and there was a strong need for an instrument to indicate absolute altitudes near the ground. Even though Rice's efforts were successful, his instrument was complicated and difficult to use when compared with the Kollsman sensitive altimeter which was introduced in the United

States about this time. To use the sensitive altimeter for absolute indications, an accurate compensation for barometric pressure at the ground level was required but the radio supplied the pilot with this information and the adjustment was very simple. In the natural course of events the sonic altimeter development was dropped and the sensitive altimeter was included in the equipment of all airplanes used for blind flying. For ordinary operation over established air routes, the sensitive altimeter has proved to be entirely adequate but there have been a number of accidents which might have been prevented by the use of sonic altimeters in airplanes. In general, the sonic altimeter would be valuable in any case of bad visibility when the pilot approaches the ground away from an established airport either intentionally or by accident. For example, it would assist in preventing collisions with the ground during flights over mountainous country by giving the pilot a definite warning of rising ground beneath him in time for him to climb over the obstruction or change his course. Over certain types of terrain it would be possible to fly by instruments at a safe altitude of several hundred feet with the sonic altimeter replacing vision as a means for maintaining contact with the ground. Prominent landmarks on the ground such as hills and valleys could be identified by noticing the rise and fall of sonic altimeter readings in relation to indications from the barometric altimeter. This general method has long been used with the marine depth finder as an aid to navigation. In descents from higher altitudes toward a low ceiling, the sonic altimeter would be a definite safety factor, especially over unknown terrain. At any time the sonic altimeter would give an independent check on adjustments of the sensitive altimeter.

Briefly summarized, the function of the sonic altimeter would be to supplement the barometric sensitive altimeter in all operations and to increase the safety of low-altitude operations both in ordinary and emergency situations. The future status of the sonic altimeter as an aircraft instrument will depend upon the answer to a single question: IS THE SONIC ALTIMETER SUFFICIENTLY USEFUL TO JUSTIFY ITS WEIGHT AND COMPLICATION? In the past the answer has been definitely NO, but with the increase in size of airplanes and improvements in sonic altimeters, it seems that the question should be reopened and settled by actual flight tests under service conditions. Certainly, if a single accident could be prevented by a sonic altimeter, a thorough investigation would be amply justified.

## OUTLINE OF SUGGESTED SONIC ALTIMETER TESTS

The flight tests suggested in the last section should be carried out with one of the sonic altimeters already developed. If these tests show that the instrument has sufficient promise, a further project should be devoted to modifications leading finally to manufacture of sonic altimeters in the United States.

The choice of equipment for sonic altimeter tests is limited to the five developments listed at the beginning of this section. The General Electric and Florisson sonic altimeters are eliminated by their use of the method of acoustic-visual coincidence which is unsuited for a routine aircraft instrument. The range of the BEHMLOT is too small for satisfactory tests, which removes this instrument from consideration. The ECHOSCOPE and the CEMA sonic altimeters have been reduced to practical instruments by refinements based on actual experience. Both use compact siren units for the signal, and an electromagnetic microphone with selective amplifiers as the receiving system. In this regard, the CEMA air-compressor supply has a definite advantage over the air-storage tank of the ECHOSCOPE for long periods of operation. Actually, a compressor could be fitted into the ECHOSCOPE system while the wind-driven compressor of the CEMA would probably have to be fitted with an electric motor drive. The indicators of the two instruments are very similar except that the CEMA unit apparently gives a continuous reading while the pointer of the ECHOSCOPE returns to zero between successive soundings. Either of these instruments should be satisfactory for the contemplated flight tests.

OUTLINE FOR A SUGGESTED INVESTIGATION OF THE VALUE OF THE  
SONIC ALTIMETER UNDER MODERN OPERATING CONDITIONS

A systematic investigation of the performance of the sonic altimeter is suggested to determine whether or not this instrument should be included in the equipment of modern aircraft. A preliminary outline of the steps in such a project is given below:

- (1) Purchase of a commercial sonic altimeter which incorporates the essential features required

in an aircraft instrument for routine use. Either the ECHOSCOPE or the CEMA sonic altimeter would be suitable for this purpose. The manufacturer should be requested to furnish all the information available on the performance of the component parts of his instrument.

- (2) Investigation of the performance characteristics of the instrument chosen. This investigation should examine the following points where reliable data have not been received from the manufacturer:
  - (a) Frequency analysis of sound from emitter.
  - (b) Sound intensity distribution measured at various angles with the emitter under conditions similar to those of actual operation.
  - (c) Total sound power from the emitter by integration from the results of (b).
  - (d) Input power required to operate the emitter.
  - (e) Sensitivity of the receiving microphone and horn system to sounds of various frequencies.
  - (f) Sensitivity of the complete receiving system to sounds of various frequencies.
  - (g) Operating characteristics of the indicating chronoscope, i.e., input required for operation, timing errors, etc.
- (3) Installation of the sonic altimeter in a typical modern airplane of suitable size.
- (4) Systematic investigation of the sonic altimeter performance over a wide range of weather conditions and with different types of terrain. This part of the investigation should have two aspects:
  - (a) Quantitative measurements by an observer using an oscillograph or similar recording instrument to make continuous records of echo intensity.

- (b) Observations made by an experienced pilot (preferably flying "under the hood") as to the value of the sonic altimeter in actual practice.
- (5) Detailed report on the results of the investigation to include
- (a) Recommendation to either extend the use of the sonic altimeter by test installations on a number of airplanes in actual service or to drop the instrument from further consideration.
  - (b) Recommendations for improvements in the sonic altimeter in case it is decided to continue the work.

## PART II

## THEORETICAL ASPECTS OF THE SONIC ALTIMETER PROBLEM

## INTRODUCTION

Acoustic measurements of altitude depend upon the use of a sender-receiver combination able to produce signals and to definitely detect the corresponding echoes in the presence of aircraft noise. The system must indicate the time interval between the signal and the echo. One of the problems in a practical instrument is the correlation of this time indication with the actual altitude. The time interval depends only on the velocity of sound and the length of the sound path. Sound velocity varies with temperature and humidity while the sound path for a given altitude depends upon the inclination of the flight path with respect to the ground, the aircraft speed, and the relative positions of the sender and the receiver in the aircraft. Since the establishment of an altitude scale on the chronoscope dial requires that a single altitude be assigned to each time interval, some set of standard conditions must be chosen for the calibration of a given instrument. Once the instrument has been calibrated, the indicated altitude as read from the dial will not be equal to the actual altitude if the existing conditions vary from the standard conditions. In the discussion which follows, any difference between indicated and actual altitudes will be expressed as a ratio and called an error. The problems of calibration and the various types of errors are considered in Section I.

During flight over sloping ground and when the aircraft climbs or descends, the flight path will be inclined to the ground surface. Such a condition has two effects on the operation of a sonic altimeter: first, the frequency of the echo is different from the signal frequency due to the Doppler Effect and, second, the indicated altitude differs from the actual altitude when the echo is received. The error due to an inclined flight path is studied in Section I and the Doppler Effect is considered in Section II.

The production and propagation of the signal and the reception of the echo present problems which belong to the field of acoustics. Section III is devoted to a brief

study of each component part of the sonic altimeter from this standpoint. An estimate of the probable limitations is made for each case.

## SECTION I - ERRORS OF THE SONIC ALTIMETER

Calibration of the sonic altimeter involves a geometrical study of the sound path. Since some definite set of conditions must be chosen, it is logical to choose the simple case of level flight over level ground with the sound propagated in straight lines. The essential features of this problem are shown in figure 1. Sound from the sender S travels over two sides of a triangle and back to the receiver R. During the sound transit the aircraft with velocity  $v$ , has moved over a distance  $vt$  where  $t$  is the time between the signal and the echo. In computing the sound path the distance  $d$ , between the sender and receiver must be added or subtracted, depending upon whether the receiver is ahead of or behind the sender. By a simple application of the law of squares, the actual altitude in terms of the other variables is given by the equation

$$h_a = \frac{ct}{2} \sqrt{1 - \left( \frac{v \pm \frac{d}{t}}{c} \right)^2} \quad (1)$$

where  $c$  is the actual velocity of sound and  $h_a$  is the actual altitude. When the chronoscope has been calibrated for the standard conditions  $c_0$  and  $v_0$  the indicated altitude  $h_i$ , as read directly from the instrument for any time interval  $t$  will be

$$h_i = \frac{c_0 t}{2} \sqrt{1 - \left( \frac{v_0 \pm \frac{d}{t}}{c_0} \right)^2} \quad (2)$$

It follows that the indicated altitude is equal to the actual altitude only under calibration conditions. For any other conditions the ratio of actual to indicated altitude is

$$\frac{h_a}{h_i} = \frac{c}{c_0} \sqrt{\frac{1 - \left( \frac{v \pm \frac{d}{t}}{c} \right)^2}{1 - \left( \frac{v_0 \pm \frac{d}{t}}{c_0} \right)^2}} \quad (3)$$

The value of sound velocity selected for calibration purposes will depend upon the average atmospheric conditions under which a given instrument is to be used. On the other hand the aircraft velocity used in the calibration is arbitrary and can be chosen either to give strictly correct readings at some one speed or to minimize errors over a range of operating conditions. The errors due to variations from calibration conditions will be discussed below.

Timing errors, due to uncertainties in measurements by the chronoscope, will affect the indicated altitude directly as shown by equation (2). This error in the time interval will usually be of approximately constant magnitude independent of the length of the time interval being measured. For an unskilled observer using the method of acoustic-visual coincidence, the timing error can have an order of magnitude of  $\pm 0.10$  of a second (reference 33), while a good electromechanical chronoscope will give a precision of  $\pm 0.001$  of a second (reference 11). If the simplified case of calibration conditions with sound velocity equal to 1,125 feet per second and

$$\left( \frac{v \pm \frac{d}{t}}{c_0} \right)^2 \ll 1 \quad (4)$$

is considered, the indicated altitude becomes

$$h_i = h_a \pm \frac{\Delta t c_0}{2} \quad (5)$$

when the timing error is  $\Delta t$  ( $\Delta t$  is taken positive if the indicated interval is longer than the actual interval). A plot of the ratio of actual altitude to indicated altitude vs. actual altitude is given in figure 5 for three values of  $\Delta t$ . The curves show that a timing error of  $\pm 0.001$  of a second will give substantially correct readings down to an actual altitude of 5 feet, while a timing error of  $\pm 0.1$  of a second introduces altitude errors larger than 20 percent for all altitudes below 250 feet. The best sound sources used in sonic altimeters up to the present time produce signals which last about 0.01 second, so that the time intervals to be measured by the chronoscope should be defined with an uncertainty less than this amount. In practice it should be possible to keep chronoscope timing errors between 0.001 and 0.01 of a second so the altitude errors will be less than 20 percent down to an actual al-

titude of about 10 feet. In any case the largest timing errors discussed here can be neglected for all altitudes greater than 200 feet.

Errors due to variations in sound velocity act on the indicated altitude as shown by equation (3). Assuming that the aircraft is flying at the calibration speed, the terms under the radicals are substantially equal since the percentage variations in sound velocity are small. The ratio of actual to indicated altitude will thus be the same as the ratio of actual sound velocity to the calibration value of sound velocity.

Sound velocity is determined by the temperature and composition of the atmosphere as given by the well-known equation (reference 32):

$$c = \sqrt{\frac{\gamma R_g T}{m}} \quad (6)$$

where

$\gamma$  =  $\frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}$

$R_g$  = universal gas constant,

$T$  = absolute temperature,

$m$  = molecular weight of air,

Over the range encountered in practice, the ratio of specific heats can be considered as constant (reference 34) so that equation (6) combined with equation (3) under the stated conditions gives

$$\frac{h_a}{h_i} = \sqrt{\frac{T_{m_o}}{T_o m}} \quad (7)$$

where the  $o$  subscripts refer to calibration temperature and molecular weight, respectively. Thus a 2-percent variation in the ratio of absolute temperature to molecular weight will cause only a 1-percent error in altitude indications.

Over the extreme range between saturated air at 40° C. (104° F.) and air with 20 percent relative humidity at

-20° C. (-4° F.), the change in molecular weight is about 3 percent, which corresponds to a 1.5-percent error in  $h_1$ . Since the composition of the air is substantially constant except for moisture content (reference 34), the effect of humidity on sound velocity can be neglected under operating conditions.

The average operating temperature will be near 290° C. Kelvin (63° F.), so that a change of 6° C. (10.8° F.) represents a variation of about 2 percent and has an effect of 1 percent on indicated altitude. Assuming that the extreme range of temperature encountered in practice is 60° C., sonic altimeter indications will vary about 10 percent from this cause. It would be easily possible to incorporate either an automatic or a manual correction on the chronoscope dial to correct for temperature changes.

Separation between the sending and receiving units will affect the calibration relation at altitudes where  $d/t$  is of the same order of magnitude as the aircraft velocity  $v$ . (See equation (1).) This effect has been studied in detail by Schreiber (reference 9). Schreiber's general method was used in the treatment presented below.

If it is assumed that the sonic altimeter is calibrated without consideration of aircraft velocity or unit separation effects, i.e., under the condition of equation (4), equation (3) becomes

$$\frac{h_a}{h_1} = \sqrt{1 - \left(\sigma_0 \pm \frac{d}{2h_1}\right)^2} \quad (8)$$

where

$$\sigma_0 = \frac{v_0}{c_0}$$

Figure 6 is a plot of equation (8) for various values of the calibration aircraft speed/sound velocity. The curves show that for altitudes over four times the separation distance and aircraft velocities less than 0.2 of sound velocity, errors due to the separation have no appreciable effect. However, for altitudes equal to or less than the separation, the errors become large. Obviously, it is possible to correct the altitude scale for the separation error in a given installation. The separation effect can become important at low altitudes with installations in large airplanes where the sender and receiver are placed many feet apart in order to reduce direct acoustic interference.

Aircraft velocity will affect the ratio of actual altitude to indicated altitude as shown by equation (3). It has already been shown that the effect of sender-receiver separation can be neglected at altitudes much greater than the separation. This is equivalent to neglecting  $d/t$  in comparison to  $v$  so that equation (3) can be written as

$$\frac{h_a}{h_i} = \frac{c}{c_0} \sqrt{\frac{1 - \sigma^2}{1 - \sigma_0^2}} \quad (9)$$

where

$$\sigma = \frac{\text{actual aircraft velocity}}{\text{calibration sound velocity}}$$

Equation (9) is plotted in figure 7 for the case of actual sound velocity equal to calibration sound velocity. Three values of calibration air speed are considered. The curves show that up to values equal to 0.4 of sound velocity, the effect of aircraft speed on indicated altitude is less than 4 percent.

Errors due to inclination of the flight path are caused by the continuous variation of the sound path length and the distance above the ground during the sound transit interval. This inclination can be due either to sloping ground or to altitude changes of the aircraft without affecting the theoretical treatment. The actual altitude to be used in comparison with the indicated altitude can reasonably be chosen as that which exists when the echo is received. Delsasso (reference 26) has studied this problem and has given a correction plot for various angles. The treatment which follows is substantially the same as that of Delsasso.

Figure 8 shows the essential geometrical features of the inclined path problem. It is assumed that the necessary adjustments to sender and receiver angles have been made to insure a satisfactory reception of the echo. A signal is emitted when the sender is at S and is received at R after traveling over the path SOR. The angle between the flight path and the ground is called  $\alpha$  and is taken as positive when the aircraft is approaching the ground surface. Neglecting the separation between the sender and receiver, the aircraft will move the distance SR in a time  $t$ . In this same time the sound pulse must travel over the path SOR. The problem is simplified by

addition of the mirror image  $S'OR'$  to the actual sound path. In the complete figure thus formed, the length of the sound path is  $SR'$  which is equal to  $ct$ . The line  $RR'$  is equal to twice the actual altitude when the echo is received. Applying the law of cosines to the triangle  $SR'R$  gives

$$4h_a^2 = (ct)^2 + (vt)^2 - 2(ct)(vt) \cos \theta \quad (10)$$

Equation (10) can be written

$$h_a = \frac{ct}{2} \sqrt{1 + \sigma^2 - 2\sigma \cos \theta} \quad (11)$$

The next step is to determine  $\theta$  in terms of  $\alpha$  by again applying the law of cosines to the triangle  $SR'R$  to obtain

$$(ct)^2 = (4h_a)^2 + (vt)^2 - 2(2h_a)(vt) \cos \gamma \quad (12)$$

Eliminating  $h_a$  between equations (10) and (12) and using the relation  $\cos \gamma = -\sin \alpha$  from figure 8 gives:

$$\cos \theta = \sigma \left[ \cos^2 \alpha \pm \sin \alpha \left( \frac{1}{\sigma^2} - \cos^2 \alpha \right)^{\frac{1}{2}} \right] \quad (13)$$

The desired expression for actual altitude is reached by substituting the value of  $\cos \theta$  from equation (13) into equation (11).

$$h_a = \frac{ct}{2} \sqrt{1 + \sigma^2 - 2\sigma^2 \left[ \cos^2 \alpha \pm \sin \alpha \left( \frac{1}{\sigma^2} - \cos^2 \alpha \right)^{\frac{1}{2}} \right]} \quad (14)$$

If the effect of sender-receiver separation is neglected, the ratio of actual to indicated altitude in an instrument for level flight over level ground becomes

$$\frac{h_a}{h_i} = \frac{c}{c_0} \sqrt{\frac{1 + \sigma^2 - 2\sigma^2 \left[ \cos^2 \alpha \pm \sin \alpha \left( \frac{1}{\sigma^2} - \cos^2 \alpha \right)^{\frac{1}{2}} \right]}{1 - \sigma_0^2}} \quad (15)$$

In this equation the proper sign has been chosen for  $\sin \alpha$  to fit the convention adopted above.

The curves of figure 9 are plotted from equation (15)

to show the effect of flight-path inclination at various aircraft speeds (calibration-sound velocity has been assumed). With the aircraft flying toward a slope, the actual altitude will always be less than the indicated altitude. The reverse situation exists when the aircraft flies away from a slope. In the limiting case of a flight path directly toward the ground surface, the indications would be about 40 percent high with an aircraft speed equal to half the velocity of sound. For a  $45^\circ$  slope the error in indicated altitude will be 20 percent for an aircraft speed equal to 0.3 the velocity of sound and about 8 percent for an aircraft speed 0.1 of sound velocity. The errors decrease rapidly as the angle of inclination becomes less. With normal landing speeds and glide paths less than  $20^\circ$ , the effect of inclination on the indicated altitude will be smaller than 5 percent. These results show that for ordinary conditions the errors due to path inclinations can be neglected.

#### DISCUSSION OF ERRORS IN THE SONIC ALTIMETER

The foregoing discussion has shown that if time intervals can be measured by a sonic altimeter system with an uncertainty less than 0.01 of a second, errors of all types can be reduced to negligible size except near the ground. Altitudes below 30 feet are more difficult to measure but by a special calibration taking into account the separation between the sender and the receiver in a given installation, accurate indications can be carried lower. Ultimately the length of the signal will become the factor which determines the lower operating limit. This phase of the problem must be attacked by design changes rather than as a matter of calibration.

In general, the inherent errors of a properly designed sonic altimeter are so small that the indications can be used with complete confidence under operating conditions.

#### SECTION II - DOPPLER EFFECT DUE TO INCLINATION OF THE FLIGHT PATH

Delsasso has analyzed the effect of an inclined flight path on the frequency of the echo when a constant frequency

sound source is used (reference 26). The treatment outlined below is taken directly from Delsasso's work.

A sound of frequency  $n_s$  sent out by the source at S would have a wave length of  $\lambda_s$  if the source were stationary; that is, one cycle would be completed in a distance equal to  $\lambda_s$ . For acoustic sounding purposes only the sound sent out in the direction SO is important. The source has a velocity component  $v \cos \theta$  in this direction, so that the distance for one complete cycle becomes

$$\lambda_s - \frac{v \cos \theta}{n_s} = \frac{c - v \cos \theta}{n_s} = \lambda_o \quad (16)$$

which is the wave length  $\lambda_o$ , that would be detected by a stationary observer at O. The corresponding frequency  $n_o$ , is

$$n_o = \frac{c}{\lambda_o} = n_s \frac{c}{c - v \cos \theta} \quad (17)$$

If the angle  $\Phi$  is less than  $90^\circ$  the aircraft will have a velocity component away from O along the direction OR equal in magnitude to  $v \cos \Phi$ . On the aircraft, the received frequency  $n_R$ , will be reduced in the ratio of the velocity of a point on the sound wave past the receiver to the velocity of sound in free air, i.e.,

$$n_R = \frac{n_s c (c - v \cos \Phi)}{(c - v \cos \theta) c} \quad (18)$$

which can be written as

$$n_R = n_s \frac{1 - \sigma \cos \Phi}{1 - \sigma \cos \theta} \quad (19)$$

This relation is more useful if  $\theta$  and  $\Phi$  are expressed in terms of  $\alpha$ . By a process like that used to determine  $\theta$  as a function of  $\alpha$  (see equation (13)),  $\cos \Phi$  can be written as

$$\cos \Phi = \sigma \left[ \cos^2 \alpha \pm \sin \alpha \left( \frac{1}{\sigma^2} - \cos^2 \alpha \right)^{\frac{1}{2}} \right] \quad (20)$$

When the expressions of equations (13) and (20) are sub-

stituted for  $\cos \theta$  and  $\cos \Phi$  in equation (19) the result is

$$n_R = n_S \frac{1 - \sigma^2 \cos^2 \alpha + \sigma \sin \alpha (1 - \sigma^2 \cos^2 \alpha)^{\frac{1}{2}}}{1 - \sigma^2 \cos^2 \alpha - \sigma \sin \alpha (1 - \sigma^2 \cos^2 \alpha)^{\frac{1}{2}}} \quad (21)$$

where the signs have been adjusted to the convention for  $\alpha$ .

Using the expression for  $n_R$  Delsasso shows that the ratio between the received and emitted frequencies  $\eta = n_R/n_S$  of equation (21) can be reduced to the form

$$\eta^2 - 2\eta \frac{1 - \sigma^2 \cos 2\alpha}{1 - \sigma^2} + 1 = 0 \quad (22)$$

A polar plot of  $\eta$  as a function of  $\alpha$  for various values of  $\sigma$  is given in figure 10. For aircraft velocities about 0.1 of sound velocity the increase in echo frequency produced by flying toward sloping ground is small, being only 20 percent for flight directly toward the ground. However, for the higher aircraft velocities the effect is much more pronounced; for example, with an aircraft velocity equal to 0.3 sound velocity flying toward a  $30^\circ$  slope will produce a 40-percent increase in the received frequency as compared to the emitted frequency.

The Doppler effect has no direct effect on altitude measurements but it becomes very important if a tuned receiver is to be used for the echo. If the tuning is made too sharp in an attempt to increase sensitivity, a relatively small slope in the ground or even a steep glide may shift the received frequency to such an extent that the echo can no longer be detected. On the other hand, if some provision is made for manually tuning the receiver in accord with a suggestion made by Delsasso, it might be possible not only to maintain the receiver sensitivity but even to make a good estimate of the ground slope below the airplane. The importance of these suggestions will have to be determined by service tests.

## SECTION III - ACOUSTICAL PROBLEMS OF THE SONIC ALTIMETER

## INTRODUCTION

Acoustical principles determine the performance of sound sources and receivers for the sonic altimeter. Acoustics must also be considered in timing the interval between the signal and the echo since a minimum number of cycles is required in each blast for a satisfactory detection of the signal in the presence of aircraft noise. The intensity losses due to spreading and absorption during propagation of the signal also require treatment by methods of sound theory. A brief study of these various problems will be given below to suggest the important limitations rather than to present a complete treatment.

Figure 11 shows the essential parts of a sonic altimeter system. A source of energy is connected to some type of transducer for converting mechanical, electrical, or compressional energy into sound. The energy is controlled by a timer which permits a short signal at definite intervals. Since the transducer must have a very high sound-power output, it is necessary to use some type of horn or reflector to give efficient coupling and to confine the energy in a properly directed cone. Once the signal has left the sender, the effects of absorption in the air and at the ground surface must be considered. A second transducing element in the receiver must convert the energy collected from the echo by a horn or reflector into electricity which can be amplified to operate the chronoscope. Since the original sound energy is first converted into mechanical energy and finally into electrical energy, the filtering system to reduce aircraft-noise effects can have acoustical, mechanical, and electrical elements or may be a combination of all three. The chronoscope is connected to the sending and receiving systems and must be fitted to the requirements of both. The discussion below will consider each of these parts of the problem and finally make an estimate of the theoretically possible performance of a sonic altimeter.

## CHRONOSCOPE

The device for timing the signal-echo interval will be considered first since the problems involved are mechanical rather than acoustical.

Chronoscopes of various types have been described in the sections on sonic altimeters which have already been constructed. A good general discussion of the subject is given by Dubois and Laboureur (reference 19). It has been noted that the oscillographic instruments of Behn, Florisson, and Nandillon and the neon discharge-tube arrangement used by Delsasso are all capable of measuring time intervals with an uncertainty less than 0.001 second. However, these devices depend upon an optical signal which requires that the pilot be looking at the dial when the echo is received. The automatic-reading electromechanical chronoscopes used in the BEHMLOT (reference 8) and the ECHOSCOPE (reference 28), are better than the oscillographic type from this standpoint, but still have the disadvantage that the pointer returns to zero between soundings. No quantitative information on the precision of these instruments is given beyond the statement that the ECHOSCOPE can measure 1/600 of a second.

Chronoscopes have long been used in the science of psychology to measure reaction times and have received their highest state of development in this field. Descriptions of modern electromechanical chronoscopes have been given by Max (reference 35) and Dallenbach (references 36 and 37). The uncertainty in measuring short time intervals is of the order of 0.001 second. The discussion of timing errors in the sonic altimeter has already shown that a precision of 0.001 second will be completely satisfactory for measuring signal-echo intervals. At present the electromechanical chronoscope must be reset for each new reading. However, the addition of a mechanism similar to that used in chronometric tachometers will make continuous reading possible. The intermittent action of both instruments is essentially the same so that the necessary refinements should not be difficult.

Electrical chronoscopes have distinct possibilities in that the precision and sensitivity can be easily controlled in an instrument with no moving parts except the indicating hand. Dubois and Laboureur (references 19 and 38) have devoted considerable effort toward the development of the time constant circuit type of chronoscope which is described in Appendix A. Since the time of their reported work, many new electronic circuit elements have become available. In particular, it would be an advantage to replace the simple neon tube-control elements by modern grid-controlled discharge tubes such as the General Electric Thyatron. The future status of the electrical

chronoscope will depend upon a balance between convenience in operation and the necessity of close voltage control in a circuit whose elements may be subject to aging effects and sensitive to vibration.

Electrical frequency meters have received much attention during the last few years. Hunt (reference 39) and Wheatcroft and Haley (reference 40) have described direct-reading frequency meters based on modern electronic technique. This type of instrument seems to have good possibilities as the chronoscope unit for sonic altimeters of the modulation types as described by Jacquet and Badin (reference 18).

At the present time the electromechanical chronoscope seems to be best adapted for use in the sonic altimeter. The precision of this instrument can be made so high that it does not limit the accuracy of altitude measurements in any way and it seems to have withstood the test of actual service in a number of installations. Chronoscopes of the electrical type show considerable promise but will require development before they are completely satisfactory. In any case, there is always the rotating hand-human observer combination with excellent sensitivity but low precision in time measurement.

#### SOME RELATIONS FROM THE THEORY OF SOUND

The theory of sound deals with small displacements of particles in a continuous medium. Figure 12 shows the essential features of the sound problem for the simplified case of a plane wave. When no disturbance is present, all the particles in planes at right angles to the x-axis are at rest in their equilibrium positions. When these particles are disturbed by a pressure gradient in the material, all the particles in a thin slice are displaced a distance  $\xi$  from the equilibrium and resist the motion by their own inertia reaction. A derivation of the wave equation for sound is outlined in Appendix B and the solution is given for the case of a sinusoidal wave. It is noted that the relations commonly used in sound theory are based on the assumption of a disturbance so small that the density and pressure changes are negligibly small fractions of the actual values. In this case of an "infinitesimal" disturbance, the wave will maintain the same shape as it is propagated through the medium. On the other hand, if the pres-

sure and density changes are too large, a wave will change its shape during propagation. This fact is important for sonic altimeter work since it places a limit to the amount of sound power at a single frequency which can be sent out from a source of given size. If this limit is exceeded, a part of the energy will be lost in higher harmonics which cannot be detected by a tuned and filtered receiving system.

Derivations of the sound-theory relations which are useful for sonic altimeter purposes are carried through in Appendix B. The quantities of most interest in waves of sinusoidal form are:

$p$  is the root mean square pressure change due to a sound wave; called excess pressure or sound pressure.

$\xi_m$ , amplitude of particle displacement due to the sound wave.

$I$ , average rate of transfer of sound energy across unit area of the wave front; called intensity.

In the succeeding discussion  $p$  will be measured in bars (one bar is equal to ~~one~~ dyne per square centimeter), displacements will be measured in centimeters, and intensity will be given in watts per square centimeter. The relation between intensity and sound pressure is

$$I = \frac{p^2}{\rho_0 c 10^7} \quad \text{watts per square centimeter} \quad (23)$$

where  $\rho_0$  is the density in grams per cubic centimeter

and  $c$ , velocity of sound in centimeters per second

For the case of normal barometer (760 millimeters of mercury) and a temperature of 20° C., the value of  $\rho_0 c$  is 42. Figure 13 shows the curves for sound pressure, particle displacement, and particle acceleration as functions of intensity. The range of intensities chosen is very high compared to those encountered in ordinary sounds since it is desired to illustrate the extremely high accelerations which would be necessary to obtain high outputs from small-size radiating areas. For purposes of

comparison, it can be noted that the maximum intensity a human being can endure without injury to the hearing organs, is about 0.001 watt per square centimeter. For a sound pressure of 0.1 atmosphere, the variation of the coefficient in the wave equation which gives the velocity of sound (see Appendix B) will have the same order of magnitude. This great a change would certainly be accompanied by considerable energy losses from the effective signal frequency. Using the intensity corresponding to a sound pressure of 0.1 atmosphere taken from the curve as a tentative limit, the maximum sound intensity in any passage of a practical sound source would be 8 watts per square centimeter. This intensity corresponds to an acceleration  $4 \times 10^4$  times gravity. Since the curves are plotted on the basis of simple sound theory the values will be approximate only. However, the difficulty of imparting such motions to a mechanical system is obvious. The actual limit of efficient operation for any given sound source would have to be determined by experiment, so it is impossible to do more than indicate the nature of the action to be expected.

The general subject of acoustic losses in high intensity sound waves has been treated by Fay (reference 41) and Thuras, Jenkins, and O'Neil (reference 42).

#### EFFECT OF SPREADING ON SOUND INTENSITY

If the output from a source of sound is confined to a cone whose apex is the source, the same amount of energy will flow across surfaces which increase in area with the square of distance from the source. This is no longer true if losses due to absorption are taken into account. Rice (reference 13) has particularly considered the effect of spreading on the sonic altimeter problem and describes many actual measurements on sound intensities from various sources. In Appendix B it is shown that, if spreading alone is considered, the relationship between sound pressure, actual altitude, and power of the source is:

$$p = 134 \frac{\cos \delta}{h} \sqrt{\frac{W}{1 - \cos \Delta}} \quad (24)$$

where

$h$  is in feet

$p$  is in bars

$W$  is in watts

$\Delta$  is in half angle of the cone of sound

$\delta$  is the angle between cone axis and the vertical

In general, the requirement to be fulfilled is that a certain minimum sound pressure must exist in the echo from the signal in order to produce a definite response from the receiving system. Thus the essential design problem in a source of sound is to achieve the largest possible output confined to a narrow beam; i.e., to make  $W$  large, and  $\Delta$  small. The angle  $\delta$ , between the cone of sound and the vertical should be set to produce the best possible echo at the receiver. This angle is determined by the ratio of the speed of the airplane to the speed of sound and the slope of the ground. In actual practice this tilt of the sound cone can be made adjustable, or fixed at some compromise angle. The alternative is to make the cone of sound so large that it will reach the receiver under all conditions which occur in operation. This last solution is unsatisfactory since a large cone angle reduces the effectiveness of the source so far as the echo is concerned. The effect of spreading on the range of a sonic altimeter will be considered later.

### ABSORPTION LOSSES

Absorption in the atmosphere reduces the intensity of sound due to friction effects in the medium itself. These transmission losses may be divided into two classes: first, direct absorption of the sound by the medium, and second, losses due to diffraction and interference resulting from nonhomogeneity and turbulence in the medium.

Except at very high intensities, such as might exist in the immediate vicinity of an intense source (reference 42), the absorption of sound per unit distance transversed is found to be proportional to the intensity of the sound. Mathematically, this leads to an exponential law for decrease of intensity with distance for plane waves, i.e.,

$$I = I_0 e^{-\mu x} \quad (25)$$

where  $I_0$  is the intensity of sound when  $x$  is zero  
 $x$ , distance measured from some arbitrary point  
 $\mu$ , the absorption coefficient

The most reliable data on this type of attenuation are those given by Knudsen (references 43, 44, and 45). Knudsen has carried out extensive measurements on the rate of decrease of sound intensity in closed chambers as a function of temperature, pressure, composition, and moisture content. His data, which are pertinent to the sonic altimeter problem, have been converted into terms of db reduction in intensity per 100 feet of distance and plotted in figure 14. These curves show that conditions of high humidity are accompanied by relatively low attenuation. This is a desirable characteristic for acoustic soundings since a sonic altimeter will be most useful in fog and storms. For high humidities the attenuation at 2,000 cycles per second is 1/4 db per hundred, and at 10,000 cycles per second the attenuation is 2 db per hundred feet. Thus a 2,000-cycle beam will be reduced to half intensity in a distance of 1,200 feet, while a 10,000-cycle beam would require only 150 feet for this same reduction. This rapid increase in absorption with increasing frequency certainly prevents the use of ultrasonic frequencies for sonic altimeter purposes and makes it desirable to use the lowest frequencies permitted by other aspects of the problem.

Information on the effects of nonhomogeneity in the atmosphere is much more difficult to obtain than in the case of direct absorption. Extended studies of the transmission of fog signals at sea have been made by Hubbard (reference 46), Milne (reference 47), King (reference 48), and Tyndall (reference 50).<sup>49</sup> Of the investigators who have studied the sonic altimeter directly, only Delsasso (reference 26) has made any specific mention of the effect of atmospheric conditions, although a number of others have suggested that violent disturbances such as storms greatly affect the operating range of a sonic altimeter. Data on sound transmission in an essentially horizontal plane can probably not be directly applied to vertical sound paths. Vertical gradients of velocity and temperature may have much worse effects on horizontal than on vertical transmission. The only conclusion that can be drawn from the

information now available is that atmospheric attenuation will fluctuate in an erratic manner and becomes greater under conditions of strong disturbances. Since one of the important functions of a sonic altimeter is to assist the pilot in bad storms, this phase of the general problem should certainly be investigated to establish quantitative limits for the conditions found in practice.

### REFLECTION AND ABSORPTION AT THE GROUND

Reflection from the ground surface forms an essential part of each acoustic sounding. The wide variation of the ground surface makes this phase of the problem very difficult to handle quantitatively. It is only possible to define the limiting cases and to sketch in roughly the general principles involved. The best possible condition is that of a hard plane surface which does not absorb any energy and reflects the sound beam in the same manner that light is reflected by a mirror. This is called specular reflection and is illustrated in figure 15a. The second type of reflection is assumed to have a maximum intensity on the perpendicular to the reflecting surface and fall off as the cosine of the angle from this perpendicular. This variation is similar to Lambert's Law of diffuse reflection in optics, and for this reason Rice has given the name of diffuse reflection to this type of acoustical phenomenon. Figure 15b is a plot showing the intensity as a function of angle in diffuse reflection. Actually, any reflection of sound will be some combination of both types of reflection depending upon the nature of the reflecting surface. Figure 16a shows a possible distribution of intensity with specular reflection predominating, while figure 16b is a similar plot showing a case with diffuse reflection predominant. An expression for the ratio between echo intensity with specular reflection and with diffuse reflection has been given by Rice. Absorption losses at the surface of the ground are taken into account by means of reflection coefficients. As derived in Appendix C, this expression is:

$$\frac{I_R'}{I_R} = \frac{K^2}{4K \tan^2 \Delta} \quad (26)$$

where  $K^2$  is the reflection coefficient with specular reflection,

K, the reflection coefficient with diffuse reflection ,

$\Delta$ , the half angle of the cone of radiation ,

Rice notes that with both reflection coefficients equal to unity the intensity ratio is 8 for a half-cone angle of  $10^\circ$ . If the specular-reflection coefficient is unity and the diffuse-reflection coefficient is 0.25 the intensity ratio becomes 32. These values illustrate the very large differences which can result from variations in the reflecting surface. In practice both diffusion and absorption effects are taken into account by means of experimentally determined coefficients.

Eisner and Krüger (reference 51) have determined reflection coefficients for sound directed perpendicular to the surface tested. Their results are summarized below:

<u>Terrain</u>	<u>Reflection coefficient</u> <u>in percent</u>
Ice	100
Water	93
Meadow	46
Forest	19-46

The worst terrain from the standpoint of the sonic altimeter is certainly a forest. It is probable that the sound frequency used will influence the absorption coefficient. As in optics, waves having wave lengths comparable to or greater than the size of obstacles they meet, easily bend around these objects. A low-frequency sound directed toward the top of a forest would be expected to penetrate farther into the trees, and, assuming equal absorption coefficients per unit of depth, would be more strongly absorbed than sound at a higher frequency. An effect which might possibly be more important is that the increased penetration at low frequencies would result in an indefinite path length with an accompanying decrease in echo intensity at any instant but an increase in duration.

The foregoing discussion shows that transmission losses along the sound path in acoustic soundings will vary from a minimum value due to the direct absorption losses which account for about  $1/2$  db per hundred feet of path length at 3,000 cycles per second to a higher value which includes not only this attenuation but a further 7

db (multiplying factor of  $1/5$ ) due to losses at the ground surface. In addition to these effects there are further reductions in intensity due to atmospheric disturbances which are indefinite but can easily amount to another 3 to 5 db (multiplying factor of  $1/2$  to  $1/3$ ). Thus for a sounding at 800 feet, transmission losses can be as much as 20 db, which corresponds to an intensity ratio of  $1/100$ . This, of course, is in addition to the spreading losses, which cause the intensity to fall off as the inverse square of the sound-path length. These rough estimates show very clearly the difficulty in designing a sonic altimeter to operate at even moderate altitudes.

### SOURCES OF SOUND

Power for the signal required in acoustic soundings can be derived from chemical, electrical, mechanical, or compressed gas supplies. With the exception of the Jacquet-Badin instrument which used a continuous sound wave modulated by the echo, all the practical sonic altimeters described up to the present time have required an intense signal of very short duration. This means that the actual source of power can work continuously at a low output to store up energy for a sudden release at the proper instant. The selection of a power source must be determined by the acoustic output possible from a unit of reasonable weight. In order to make a fair comparison, all the additional equipment required for the sonic altimeter must be considered, including storage and control mechanisms. Beyond doubt the pistol sound source of Behm is excellent from the standpoint of weight provided the number of soundings required is not too great. However, any advantage of this sort is nullified by the complex nature of the emitted sound which prevents the use of an efficient receiver. In practice, the power actually used to operate the transducer will usually be either in form of electricity or compressed gas. This is true whether the actual transducer is a mechanically excited diaphragm, an electrical loudspeaker, a whistle, or a siren. It is possible to estimate the probable weights of the units required for energy storage in both cases and to estimate the weight of the actual transducer, but unless the weights of voltage changers, motors, air compressors, etc., are known, no definite conclusion can be reached. Up to the present time, the range of sonic altimeters with electrical sound sources has been so low compared to that of air-driven units that there is a

reasonable basis for assuming that this latter type has a definite advantage in practice. On the other hand, a completely electrical sonic altimeter could be operated from the normal aircraft power supply, and thus could afford a considerable weight handicap in the transducer unit as compared with an instrument requiring a special compressor installation. A definite answer to the question of the best power supply must wait for a careful design of each type to be worked out on the basis of a comparable performance.

For efficient operation of a sonic altimeter the acoustic energy from the sound source must be so directed that the receiver is in a region of relatively high intensity when the echo returns. Any energy which is distributed over areas outside of possible receiver positions is no more available than if it were lost by absorption. This leads to the necessity of a directive sound source. So far as the free atmosphere is concerned, the actual emitter is either the mouth area of some type of concentrating unit or the actual surface of a diaphragm. For in any case the directionality of the sound output will depend upon amplitude and phase relations over the radiating surface. In general, it is impossible to calculate the intensity distribution and sound-power output from an arbitrary source. However, the simplified case of a vibrating disk placed in an infinite plane baffle will lead to results similar to those found in practice. Appendix D outlines the treatment presented by Morse (reference 32) for radiation from a disk. Figures 17 and 18 show intensity distributions for several ratios of wave length to disk radius. The intensity scale is arbitrary, but for comparable conditions in each case. With a wave length five times the disk radius, the intensity distribution is almost hemispherical while most of the energy is confined within a cone of  $30^\circ$  half angle if the wave-length-radius ratio is 2. When the wave length is made equal to the radius the radiation cone half angle is about  $15^\circ$ . This angle becomes about  $10^\circ$  when the radius is twice the wave length. As noted above, the calculated distributions are not realized in practice but the general trend of increased directionality with decreasing wave-length-radius ratio checks with experiment. Goldman (reference 52) observed that the actual cone angle of radiation is 1.5 to 2 times the calculated angle.

The integration necessary to calculate the total sound output from a vibrating disk is discussed in Appendix D.

Reduced to simple terms, the relation between the displacement amplitude of the disk, power output and radius for 3,000 cycles per second is

$$x_m = \frac{0.0203}{a} \text{ centimeters per watt radiated} \quad (27)$$

Assuming that it is desired to concentrate the radiation from a sonic altimeter source in a cone with a half angle of  $20^\circ$ , the diagrams of figure 18 show that the disk radius should be about twice the wave length emitted. Rice found that an output of about 85 watts was produced by his sound source at 3,000 cycles per second. So, taking 100 watts as a reasonable output for a hypothetical instrument, the required disk radius will be about 23 centimeters. The disk must vibrate with an amplitude of 0.09 centimeter. This corresponds to an acceleration amplitude of about 32,000 times the acceleration of gravity. The mechanical difficulties of imparting such an acceleration to a rigid disk 50 centimeters in diameter, are obvious. With these figures in mind, it will be seen that a diaphragm similar to that used by Nandillon (reference 18) has serious limitations as to the possible output.

The art of designing elements to efficiently carry sound power from a small transducer to the free air, is well developed and has been discussed by many workers (references 53, 54, 55, 56). It is possible to make very great improvements over the freely exposed diaphragm, but even if the necessary diaphragm acceleration could be reduced by a factor of 1,000, it would still be difficult to obtain an output of 100 watts with good directionality from a small electrically driven unit. Up to the present time the efforts of acoustical engineers have been largely directed toward the production of units with uniform response over a wide frequency range. The loudspeaker described by Wente and Thuras is typical of the results obtainable (reference 57). Their unit produced 15 watts of sound energy with an over-all efficiency of 50 percent. The weight of the apparatus was about 15 pounds, which gives an output of about 1 watt for each pound of weight. It is to be noted that the loudspeaker of Wente and Thuras was designed for a wide frequency range and given a continuous rating, so it is certain the performance could be greatly improved for sonic altimeter purposes by restricting the range and using an intermittent rating. Another possible solution of the sound-source problem lies in the use of an electrically driven vibrator similar to those

of automobile horns. Difficulties from a slow building up of the sound to full intensity are to be expected for such devices.

Pulse length in the signal should be as short as possible from the standpoint of interval timing. However, best operation of a receiving system is attained when the echo has a well-defined frequency over a long period. The problems introduced because of these conflicting requirements appear both in the fundamental physical theory and in the mechanical design of a particular sonic altimeter. From the physical standpoint, the concept of radiation at a single frequency cannot be realized except in an infinitely long-wave train. The starting and stopping of the radiation involves a spread of energy over a band of frequencies which increases in width as the number of cycles in the pulse decreases. The derivation of the relation between intensity and wave length is outlined in Appendix E. Figure 19 shows the corresponding plots for number of cycles between 1 and 32. For a pulse consisting of a single cycle, the energy is distributed from very low frequencies to a high frequency limit which is almost twice the frequency of the original pulse. The energy becomes more concentrated toward the pulse frequency as the number of cycles is increased, until with a pulse length of 16 cycles, the energy is spread over a range which extends less than 5 percent on either side of the pulse frequency. The plot shows that any sonic altimeter signal should contain at least 16 cycles if the receiver is to be sharply tuned and that there is a comparatively small percentage gain in intensity by going to larger numbers of cycles. This conclusion agrees with the results found by experiment in that actual sonic altimeters have used frequencies between 1,500 and 3,500 cycles per second with a pulse duration of about 0.01 second.

Air-driven sound sources such as whistles and sirens have a definite advantage over units which use diaphragms since there are no mechanical parts to be vibrated at sound frequency. The mechanical limitations are thus reduced but the losses which accompany high sound intensities are still present. The problem of directional emission from air-driven sources is not susceptible to mathematics but the general principles with regard to the influence of the wave-length-radius ratio will still be valid as applied to the horn opening. It will certainly be necessary to test each combination of transducer (in this case the whistle, siren, or other device for producing sound from the energy

of compressed air) and coupling element (horn, megaphone, parabolic reflector, etc.) under the actual service condition. This could be done by making a full-scale model of the aircraft parts near the sound source and carrying out intensity measurements with the cone of sound directed upward to avoid interference effects from ground objects. It seems reasonable to direct the beam of sound forward toward position of the receiver when it is excited by the echo and to eliminate the useless side parts of the sound cone by proper shaping of the horn used to couple the transducer to the atmosphere. Such a design will entail little extra labor since the details must depend on experiment in any case.

Rice (reference 13) has given the only available quantitative data on the performance of whistles as sound sources for acoustic sounding purposes. He found that a freely exposed whistle transformed about 5 percent of the input energy into sound while under similar conditions the efficiency of a siren was only about 1/10 of this amount. The total output from a whistle which gave 152 watts in free air was reduced to 86 watts when it was placed in a directive megaphone. In contradiction to Rice's conclusion that the siren is inferior to the whistle, is the fact that the best developed sonic altimeters use sirens as the sound source at the present time. It may be that the siren is well adapted to use with a directive horn and that Rice would have obtained better comparative results from this device if his tests had been carried out with a megaphone instead of in free air. In any case a quantitative performance investigation for various types of air-driven sound sources in combination with directive elements specially designed for the sonic altimeter would be of great assistance in future work.

### MICROPHONES

Microphones act as transducing elements to change acoustic energy into electrical energy. Such a device is an essential part of every sonic altimeter except those instruments using aural detection. Microphones are of two general types - the carbon-powder type and the generator type. Carbon-powder microphones are ruled out for sonic altimeter purposes by their extreme sensitivity to mechanical disturbance (reference 19). The generator microphones which are commercially available, can be classified

as electrostatic, electromagnetic, and piezoelectric or crystal types. The electromagnetic units can be subdivided into moving iron (the inverse of the common telephone receiver), moving coil, and ribbon types. A good criterion of performance for microphones is the voltage delivered to the grid of the first amplifier tube for one bar sound pressure on the unit. The tabulation below shows representative sensitivities for the various types of microphones:

<u>Type</u>	<u>Millivolts per bar</u>	<u>References</u>
Moving coil	10	58 and 59
Condenser	3	58
Ribbon	1	60
Piezoelectric	0.1	58

The microphone used by Delsasso (reference 26) is a special type which cannot logically be fitted into the above classification. His unit had a satisfactory sensitivity and selectivity for operation on a lighter-than-air craft but was not tested on an airplane.

In addition to the sensitivity, the threshold (minimum sound pressure for a definite indication) is also useful. This limit is set by uncontrollable erratic effects in the amplifiers and can be safely taken as 10 microvolts for pure tones. On this basis the thresholds for various types of microphones become:

<u>Type</u>	<u>Threshold in bars</u>
Moving coil	0.001
Condenser	.003
Ribbon	.01
Piezoelectric	.1

It is to be noted that the moving-coil microphone was the only one of this group fitted with an acoustic coupling network so that the thresholds for the other types would probably be increased if proper coupling systems were used.

For purposes of comparison it can be noted that the threshold pressure for the average human ear is 0.0005 bar. Thus the ear can detect a sound pressure about half of that required for the most sensitive microphone on the basis adopted above.

When the high noise level existing about an airplane in flight is considered, it is obvious that threshold pressure is not the limiting feature of microphones for acoustic soundings. The important properties are insensitivity to shock and vibration with an ability to select a pure tone echo out of a high intensity background of noise. The electromagnetic type of microphone is probably best from the standpoint of ruggedness and the ability to tune out undesired sounds.

#### MICROPHONE COUPLING SYSTEM

Sonic-altimeter experiments have uniformly demonstrated that the altitude at which reliable echoes can be detected increases very greatly when the aircraft noise is reduced in any way. This definitely proves that the range is limited by the ratio of signal intensity to noise interference rather than by the absolute intensity of the echo. It therefore becomes important to determine the intensity distribution with frequency of noise from various sources on the aircraft. This problem has been studied by many investigators (references 61, 62, 63, 64, 65, 66, 67, and 26). The essential result of these experiments for sonic altimeter purposes is that intensities for frequencies over 1,500 cycles per second are relatively low. Since a microphone sensitive to frequencies lower than 1,500 cycles per second would continually receive excitations from the aircraft itself, a very high intensity would be required before the sounding signal could be detected. This effectually prevents the use of such low frequencies and requires that the source emit a signal at a high frequency where the intensity of aircraft noise is relatively low.

Horns as applied to microphones are usually for the purpose of increasing the sensitivity by collection of sound energy from a larger area. In the sonic altimeter case, the problem is one of selectivity rather than sensitivity. Thus the coupling element should be chosen on the basis of its directional properties rather than its power to collect more energy from the atmosphere. The same gen-

eral principles apply in studying receiving horns as in the case of sound sources. Many different shapes of sound collectors have been studied. Parabolic horns are quite directional and amplify the sound pressures five or six times at frequencies between 1,000 and 3,000 cycles per second (references 68 and 69). Exponential horns give more amplification but the directional effects are not so well defined, especially at low frequencies (reference 70). This is a general characteristic of all types of horns so that the ability to collect sound energy from one direction while disregarding sound from other directions, cannot be relied upon to give freedom from interference due to low frequency sounds produced by the aircraft. As in the case of sending horns, the best design must be determined by experiments made under actual operating conditions. It is probable that conical and parabolic horns will be preferable to exponential horns.

### FILTERS

Filters are required in the receiving system of a sonic altimeter since it is impossible to eliminate low-frequency sounds by means of directional horns. There is, of course, the possibility of using a very selective microphone diaphragm but this expedient could easily give trouble due to Doppler effects or slight changes in the source frequency. In addition, a sharply tuned mechanical system is easily excited at its own natural frequency by shocks. Improper operation from these natural frequency effects must be prevented by the use of electrical filters. It follows that a practical sonic altimeter system will almost certainly incorporate some type of filter.

Acoustic filters have been analyzed by many investigators and the fundamental principles are well known (references 71, 72, 73, and 74). The theory of electrical filters is also well worked out and is available in a concise form (reference 75).

In general, filters can be designed to have any desired characteristic. However, there is one unfortunate characteristic in common for all filtering systems. That is, the time constant of the filter becomes longer as the pass band of frequencies is made smaller. Thus, if the pass band is too narrow, the time constant may become so long that a short pulse applied to the input will appear

greatly reduced at the output terminals of the filter. This problem will probably not become serious for sonic altimeter work since the frequencies to be eliminated are lower than the signal frequency and a high pass-band type of filter can be used.

#### DISCUSSION AND CONCLUSIONS

Various factors which are important in the problem of acoustic soundings have been considered above. It has been shown that a well-designed modern chronoscope will introduce no appreciable errors in the indications of a sonic altimeter. Similarly, microphone sensitivity is not an important factor in sonic altimeter performance. The most important limitation is the intensity of sound due to the aircraft which cannot be separated from the echo by means of a filter system. This residual sound intensity from aircraft noise determines the absolute magnitude of the sound pressure required for reliable acoustic soundings. This minimum sound pressure will vary from aircraft to aircraft but once it is determined for a particular case, the operating range of a sonic altimeter depends only upon the power and intensity distribution of the sound source. With these factors made definite, approximate operating limits for a sonic altimeter can be determined.

The greatest altitude will be obtained with still air over a surface such as ice or smooth water, which gives perfect specular reflection. The other limit of the operating range will occur over strongly absorbing terrain such as a forest when violent atmospheric disturbances exist. It is of interest to estimate these operating extremes approximately in order to determine the general possibilities of the sonic altimeter, and also to see how closely the instruments which have already been constructed approach the theoretical limits.

The assumptions required for estimating ranges of operation are approximate since exact data are lacking. However, the data used in the calculations will be consistent with the information now available. Rice (reference 13) found it possible to construct a whistle and megaphone combination which confined the sound radiation within a cone or half angle equal to about  $20^\circ$ . Rice also determined that under cruising conditions the human ear with a proper megaphone and filter system could identify

an echo with a sound pressure of 2 bars at 3,000 cycles per second. This should be approximately the same as the pressure required by a good microphone system under the same conditions. The data of Knudsen (reference 44) show that atmospheric absorption in still air produces an attenuation of  $\frac{1}{2}$  db per 100 feet of sound path. Upon the basis of qualitative information given by Delsasso and others, it is reasonable to assume that the attenuation due to violent atmospheric disturbances may increase to 2 db per 100 feet of path. Eisner and Krüger (reference 51) give a reflection coefficient of about 0.2 for the worst condition of a forest surface. (This corresponds to a reduction in intensity of 7 db.)

The middle column of the table below contains a range of assumed power outputs for the sound source of a sonic altimeter which confines the energy to a cone of  $20^\circ$  half angle. The left-hand column gives the estimated limit of operation for a requirement of 2 bars sound pressure at the receiver if the reflection is specular with no absorption and the attenuation is  $\frac{1}{2}$  db per 100 feet of sound path. This represents the best possible operating condition for the given sound pressure. The right-hand column is calculated in a similar manner except that the attenuation is taken as 2 db per 100 feet of sound path and the reflection coefficient at the ground is 0.2, which approaches the worst operation condition.

Maximum altitude (best condition) <u>feet</u>	Power <u>watts</u>	Maximum altitude (worst condition) <u>feet</u>	<u>Best altitude</u> <u>Worst altitude</u>
500	10	175	2.9
650	25	225	2.9
780	50	265	2.9
935	100	300	3.1
1,025	150	330	3.1
1,300	500	410	3.2

This table nicely summarizes the possibilities and limitations of the sonic altimeter. The ratio of maximum altitude for best conditions to the maximum altitude with

worst conditions has a value of about 3 for the entire range of power outputs considered. With increasing power the range increases, but much more slowly with high powers than for lower powers. Thus the gain in maximum altitude between 500 and 780 feet for a power increase from 10 to 50 watts would probably be worthwhile, but the gain from 1,025 feet to 1,300 feet as the power is changed from 150 watts to 500 watts, represents a rather small percentage increase for the added weight and complication required. The range of 935 feet for 100 watts power checks well with the results of Rice who obtained an operating range of 800 feet with a power of 86 watts. The other calculated maximum altitudes for less than 150 watts power agree well with experimental results already reported. No quantitative data are available on the power of the sound sources used but the published descriptions indicate that the outputs probably fell within the range indicated above.

The calculations used in computing the table should give a fairly reliable value of the maximum operating altitude under the best conditions, but the attenuation factor for disturbed atmosphere is very uncertain. A determination of this attenuation factor over a wide range of conditions would be a valuable addition to the art of acoustic soundings.

All the values given in the table are based on a required sound pressure of 2 bars in the echo. Since any reduction in this required sound pressure will be reflected as a direct increase in operating altitude, it is very desirable to make quantitative measurements of the sound pressure actually required for echo detection in modern aircraft. It may be that with engines removed from the fuselage and careful streamlining the sound pressure required for echo detection has been substantially reduced. If this is the case the sonic altimeter will become a very attractive instrument for use in routine operations.

## APPENDIX A

## DESCRIPTIONS OF SONIC ALTIMETERS

## Behn-Luftlot and Behnlot

(References 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12)

The TITANIC disaster of 1912 started research upon the location of icebergs by means of sound waves. In the course of these experiments it was found that the sonic method could be readily adapted to marine depth finding. One of the leaders in this field was Dr. Alexander Behn of Germany, whose work resulted in the Behn ECHOLOT. The shock of an explosion served as the source of sound but later modifications used mechanically or electrically excited diaphragms for this purpose. The obvious method of detecting the echo by ear and timing the interval between the signal and the echo with a stop watch was unsatisfactory because of the short-time intervals involved. As a consequence, Behn developed a precise chronoscope (Kurzzeitmesser) actuated by electrical impulses from carbon microphones excited in proper sequence by the signal and its echo.

Soon after 1920, Behn started to apply the principles of the ECHOLOT to the problem of altitude measurement in aircraft. Behn's first LUFTLOT was developed in 1926 and used in the "Graf Zeppelin". This instrument, which was very similar to the marine installations, was suited to airship use by a number of changes and was later adapted for installation in airplanes.

The essential parts of the LUFTLOT as used for a series of airplane tests in 1930, are described below. The source of sound was a pistol for firing blank cartridges. This unit was mounted outside the fuselage as shown in figure 20. A carbon microphone located on the other side of the fuselage (fig. 21) acted as the detecting element in the receiving system. Figure 22 shows the external appearance of the indicating and control units. The desired information was conveyed to the observer as a sharp deflection of a small spot of light in passing over a translucent screen parallel to a scale graduated directly in altitude units. A typical sounding is recorded photographically in figure 23. After the signal has been released

the line produced by the light spot appears at 1. The return of the echo occurred at 2 and the spot returns to its normal condition as at 3.

Figure 24 shows diagrammatically the working parts of the Behm LUFTLOT chronoscope. The signal is produced by a cartridge fired from the pistol 10. Simultaneously, a contact is broken in the circuit of the relay 8 which causes the release of an armature 1. When this armature is released the cantilever spring 2 gives the system 7 an impulse which causes it to rotate about an axis in the plane of a mirror attached to the system. As it rotates, the mirror reflects the focused image of an incandescent lamp on a translucent screen and thus produces the effect of a line of light to an observer. This line of light is seen as parallel to a graduated altitude scale. When the echo is received by the microphone 9, the reed 4 of the electromagnetic oscillograph 3 is excited and moves the small lens 5. This motion of the lens causes a deflection of the bright line as shown at 6. An automatic control system returns the mirror to its initial position after each sounding.

The optical chronoscope as described above was apparently very successful in the marine depth finders but the requirement of constant attention from the observer was a disadvantage for aircraft use. This situation has been somewhat improved in a modification of the LUFTLOT called the BEHMLLOT (reference 8).

The later Behm instrument as described in 1935 differs principally from its predecessor in that a completely mechanical chronoscope is used. This chronoscope does not require direct observation by the user at the instant of the echo, since a hand remains at one reading until the next sounding is started.

Figure 25 is a diagram showing the essential parts of the BEHMLLOT. The pistol 1 is automatically fired at fixed intervals by the electric motor 3 after the switch 4 is closed. The microphone 2 is so located that it will be strongly acted upon by the signal. This microphone is so connected that the vacuum-tube amplifier 14 connected to the receiving microphone 13 will not transmit an impulse to the chronoscope during the signal. In addition, the microphone 2 causes the relay magnet 5 to release the armature 6. When 6 is released the spring 8 immediately starts the rotor 7 which carries the

pointer 10 over the scale 11 at uniform speed. While the rotor is moving the signal travels to the earth and back as an echo over the path 12. When the echo strikes the receiving microphone an electrical impulse is generated which acts on the relay magnet 16 and causes the mechanical brake 17 to stop the rotor. Since the position corresponds to the lapse of a certain time interval, the scale can be graduated directly in altitude units. This reading will remain fixed until the user wishes to make another sounding. Figure 26 is an external view of the BEHMLOT indicator, showing that the unit can be included on the conventional instrument board without special adapters.

In practice, the Behm instruments had an operating range between 20 and 100 meters. In a series of flight tests described by Schreiber (reference 9), the altitude readings were found to have a mean error of  $\pm 3.5$  meters. The instruments had a weight of about 34 pounds.

#### Rice (General Electric) Sonic Altimeter

(References 4, 10, 11, 13, 14, 15)

About 1929, Mr. C. W. Rice of the General Electric Company (Schenectady, New York), started experiments that led to a working sonic altimeter for airplanes which he described in 1931 (reference 10). Rice lacked the background of sounding experience which had been available for the earlier work of Behm. His instrument lacked the precise mechanical timer of the German ECHOLOT, but the source of sound and the receiving system were found to be very efficient in actual flight tests.

Figure 27 shows the working parts of the Rice Sonic Altimeter. The source of sound is a specially designed whistle which emits a note of 3,000 hertz. This whistle is operated by compressed gas from a supply tank at 50 pounds per square inch. The pressure inside the tank is maintained by a check valve in a line connected to one of the engine cylinders. Figures 28 and 29 show an actual installation of whistle and supply tank. A motor-driven control mechanism is arranged to open the whistle valve for a blast of 10 to 30 cycles once every 2 seconds. The echo is received directly by the observer with the aid of a pair of stethoscope earpieces connected to a megaphone.

A properly designed acoustic filter is connected in the line to reduce the effect of parasite noise from the airplane and its power plant. Altitudes are estimated with the aid of a timer whose pointer rotates at constant speed over a scale graduated directly in distance units. The mechanism is so designed that the pointer passes over the scale zero when the whistle blast occurs so that the observer merely has to note the exact position of the pointer when the echo is heard. Since the time intervals are short, an accurate reading of altitude requires close attention on the part of a trained observer. This situation is especially bad at low altitudes, and to remedy it a bleeder tube is connected between the whistle megaphone and the receiving line. The bleeder enables the observer to hear the signal so that with a reasonable amount of practice he can judge his altitude directly from the time interval between the signal and the echo without looking at the timer.

An extended series of tests with the G. E. Sonic Altimeter installed in an Army observation airplane showed that reliable soundings could be carried out up to 800 feet under cruising conditions over all types of terrain. With the engine throttled for gliding, the maximum operating altitude increased to 1,400 feet. It was found possible to make blind landings based on direct judgment of the time interval between the signal and the echo.

The original apparatus had a weight of about 45 pounds when installed. The sending and receiving units were somewhat cumbersome but could be satisfactorily installed in airplanes of moderate size.

Brombacher (reference 7) notes that the G. E. Sonic Altimeter was later modified to use an electrically driven diaphragm as the source of sound with an electrical receiving system connected to the regular radio head set. This modification was made for blind landing and has a range of about 100 feet. No further information on these changes is available in the literature at the present time.

#### Florisson (SCAM) Sonic Altimeter

(References 4, 11, 16, 17, 18)

As early as 1922, Florisson of France had obtained good results with sonic depth finders for marine sounding.

He was later especially identified with the use of super-sonic frequencies for this purpose. He became interested in the sonic altimeter problem for airplanes and made flight tests on a working instrument in December 1931. His work roughly paralleled that of Rice in the United States, and his installation was similar to the General Electric apparatus.

Florisson used a compressed-air whistle as the source of sound. Reception was carried out by means of a sound collector and tube system leading to earpieces for the observer. Three types of chronoscopes were designed. The first type used a "false signal" generator which could be adjusted to produce a sound similar to the signal at the instant when the echo returned. This adjustment required a manual setting of a control on a scale graduated in altitude. The second type of chronoscope proposed to use an optical oscillograph arrangement to produce a light spot traveling at uniform speed over a circular path parallel to an altitude scale. This spot passed through zero when the signal occurred and a radial displacement of the spot indicated the return of the echo. Finally Florisson used a pointer passing through the zero of a scale at the instant of the signal and whose position on the scale at the instant of the echo gave the altitude directly. Léglise (reference 18) notes that probably only the last scheme was applied in actual flight tests.

Florisson's method of "Acoustic Coincidence" using a "false signal" generator, is illustrated in figure 30. The source of sound *e* has a whistle *s* which is supplied with air from a chamber *C* when the electromagnetic valve *S* is opened. *C* is connected to a compressed-air line through a restriction which permits a sufficient supply to accumulate between soundings but will not operate the whistle directly. This arrangement gives a sharply defined whistle blast since the sound must stop when the chamber *C* has been emptied. The echo is picked up by the horn *r* and is carried to the earpieces by a sound-insulated tube *T*. A sound filter *F* placed in this line serves to reduce the effect of parasite noise. The sound tube is branched at *b* and the branch is connected to the electrical "false signal" generator *E*. *R* is an adjustable construction which makes it possible to adjust the "false signal" intensity to the best operating level. An electromagnetically operated valve *S'* in the sound line is designed to reduce the disturbance due to direct transmission of sound from the emitter to the receiver.

The automatic-control mechanism has a clockwork operated cam 4 rotating in the sense shown in figure 30. A fixed contact 1 is closed momentarily when the indentation 3 passes under the follower spring 2. This contact allows current from the battery B to flow through the exciting magnets of the valves S and S', thus producing the signal and simultaneously excluding it from the sound tube during the time of emission. The arm 5 carries contacts 6 which close and produce the false echo when the indentation 3 passes under the spring 7. When the operator has completed the adjustment to bring the false echo into coincidence with the echo, the corresponding altitude is indicated by the pointer 8.

Details of the valve used to release the signal are indicated in figure 31. When the control contact 1 of figure 30 is closed, the winding around the pole piece 9 is energized and attracts the armature 10 which displaces the slide valve 16 the distance  $a$  by means of the rods 11 and 15 acting through the pin 14 and the yoke 13. This action moves the slide from position I to position II, so that air pressure in the chamber C suddenly forces the valve completely open to position III against the spring 12. When the air pressure has been released through the whistle this spring sends the slide back to its original position I in preparation for the next signal.

A point particularly mentioned by Florisson in connection with his apparatus, was the use of light coverings  $p$  and  $p'$  over the emitter and receiver, which preserved the shape of the aircraft surface and prevented sound disturbances due to air rushing past the horn openings.

The essentials of the oscillographic chronoscope proposed by Florisson are shown in figure 32. This apparatus is designed for use with the sending and receiving system already described up to the point where a microphone is substituted for a human ear as the sensitive element. The echo acting upon the microphone produces an output which is passed through an electrical filter  $F_e$  to reduce parasite disturbances and an amplifier  $a$ . The output of the amplifier is connected to an oscillograph element 8 by means of the slip rings 13 and 14. This oscillograph rotates at constant speed on the same shaft as the control cam. The oscillograph mirror is illuminated from an incandescent lamp 12 through the stop 11, the lens 10, and the totally reflecting prism 9. After the mirror 7 a prism 5 carried on a rotating arm, directs the light

spot onto a translucent screen with a circular graduation in altitude. The mirrors are so phased that the light spot passes through zero when the signal is released. With this arrangement a sufficiently strong echo will cause a "jog" in the otherwise smooth circular line of light appearing to the observer and thus indicate the altitude reading.

The scheme actually used in the Florisson-SCAM sonic altimeter is identical with that described in connection with the Rice-G.E. Sonic Altimeter. An exposition of the particular apparatus has already been given in the body of this report. Figure 33 shows the appearance of the indicating unit, while figure 34 indicates the essential features of an actual airplane installation.

Actual flight tests showed that the effective altitude range of the Florisson-SCAM instrument is about 150 meters under cruising conditions and about twice this with the engines throttled. Soundings could be carried on down to 5 or 10 meters about the ground. The altimeter itself had a weight of 8.7 kilograms, while the compressor and accessories added 5.4 kilograms.

#### Dubois-Laboureur Sonic Altimeter

(References 4, 11, 18, 19, 20, 21, 22, 23, 24)

Dubois and Laboureur of France designed a sonic altimeter for aircraft in 1931, and made flight tests in July 1932, with a vibrating membrane emitter. They have particularly directed their efforts toward the development of compressed-air sound sources and electrical chronoscopes.

Dubois and Laboureur used both whistles and sirens as emitters. The whistles were similar to those already discussed except for the control valve which was identical with that used on the siren to be described. Details of the siren are indicated in figure 35. Compressed air is supplied from a tube at X (upper). A sound blast is produced by the rapid movement of the piston valve T from one end to the other of the cylinder C. The conducting sections a and b separated by an insulating piece, are so located with respect to the brushes d, that a chronoscope circuit is broken during the emission time of the siren. A control system not shown in the figure operates the piston valve at automatically spaced intervals.

The disk D is rotated at constant speed by a governor-regulated electric motor. A series of equally spaced holes o, in the periphery of this disk comes successively into coincidence with the hole O' in the casing B. The motor runs at a speed of 3,000 r.p.m., which gives a frequency of 1,500 cycles per second. The passages o, o' are oblique to the axis of the disk in order that the drag torque due to the air flow will be balanced out by an equal driving torque. This feature makes it possible to reduce the power required for the siren motor.

Dubois and Laboureur found that electromagnetic microphones were well suited for use in aircraft since both the resonance frequency and damping are controllable. The microphone characteristics were so chosen that the emitter frequency was located within the resonance range of the microphone but was well away from the peak. This arrangement gave the advantage of increased sensitivity but made it possible to filter out natural frequency disturbances of the microphone excited by shock. Figure 36 is a cross section of a microphone used by Dubois and Laboureur. A properly tuned diaphragm M clamped between annular damping rings of rubber is held at the proper distance from the pole pieces p. The pole pieces are excited by the permanent magnet A and carry the pick-up coils b. A clamp nut E makes it possible to control the sensitivity of the microphone by adjustment of the air gap.

Figure 37 is a circuit diagram of the Dubois-Laboureur electrical chronoscope. Fundamentally, the instrument measures the voltage developed across the plates of a condenser which is charged from a constant potential source through a fixed resistance during the time between a signal and the corresponding echo. The constant potential is obtained by the use of a voltage-regulating neon tube  $N_2$  and a resistance across the battery P. A potentiometer tap from this resistance is in series with a second neon tube  $N_1$ , a resistance r and the primary of a transformer  $T_1$ . The circuit in parallel with r includes a resistance  $\rho$  which can be varied with a tap switch, a fixed condenser C, and the grid cathode of a vacuum tube.

The function of the tube  $N_1$  is that of a relay. This tube has the characteristic of becoming an electrical conductor when the voltage across its terminal exceeds a certain amount. The discharge is maintained until the terminal voltage becomes less than some lower limit. In the chronoscope circuit the constant voltage applied to  $N_1$  is between the breakdown and the extinction values.

When a signal is sent out the valve motion breaks the circuit between the contacts  $d$  while the insulation  $i$  is passing. This momentary break in the current from the battery  $P_1$  causes the relay  $S$  to close contacts  $p$  and  $p'$  and also includes a momentary pulse of voltage in the secondary of transformer  $T_1$ . The contacts  $p$  completely discharge the condenser  $C$  while the contacts  $p'$  short circuit the microphone during the emission period. The additional voltage applied to  $N_1$  by the secondary transformer  $T_1$  is sufficient to break down the tube and start a constant current flowing in the resistance  $r$ . This current is in the proper direction to make the vacuum tube grid positive with respect to the cathode. With a voltage drop across  $r$  the condenser  $C$  is charged through the resistance  $\rho$  and the vacuum tube which conducts when the grid is positive. The primary of the transformer  $T$  is connected to the microphone through another transformer and a filter (not shown), so that when the echo returns a voltage is induced in the secondary. This voltage is rectified by a copper-oxide unit and acts through the condenser  $C_1$  to extinguish the relay tube  $N_1$ . When this occurs the voltage drop across  $r$  disappears and the charge acquired by the condenser  $C$  remains constant since the vacuum-tube resistance becomes practically infinite to a reversal of current in the condenser circuit. Under this condition the grid  $L$  is maintained negative with respect to the cathode by an amount equal to the charge on the condenser  $C$ . This grid voltage determines the current flowing in the plate circuit of the vacuum tube as measured by the meter  $M$ .

The net result of the actions outlined in the last paragraph is that the reading of the plate-circuit meter after the return of an echo is a measure of the time interval between the signal and the echo. When the condenser  $C$  is discharged the plate current has the value corresponding to zero grid, i.e., to a zero-time interval. This current is larger than that for any negative grid bias, so a calibration of the plate meter in altitude will necessarily be "backward" with respect to the current scale. The rate at which the condenser charges for a given voltage across  $r$  will be slower as the size of the resistance  $\rho$  is increased. It follows that the altitude scale can be controlled by a simple change in  $\rho$ .

The instrument actually constructed had three adjustments corresponding to three positions of a control button.

The first position corresponded to a full-scale altitude of 250 meters. In the second position the sensitivity remained unchanged but by a special circuit arrangement, the indicating hand did not return to zero between sounding. The third control position increased the sensitivity to 90 meters for a full-scale reading. Soundings were repeated every 2 seconds on the high-altitude scale, and every 0.7 second on the low-altitude scale.

With the circuit described above, the necessary discharge of the condenser before each sounding caused a corresponding return of the indicator hand to the zero altitude reading. This action was especially objectionable for high readings. This defect was overcome by means of an auxiliary circuit. Figure 38 shows this arrangement. A condenser *c* is connected in parallel with the chronoscope condenser *C* of figure 37. A cam-controlled contact is connected at *k* and operates to keep the circuit open except for an instant before *C* is discharged for a new sounding. The auxiliary condenser is made so small that its charging current does not appreciably affect the operation of the chronoscope as already described. In this manner the voltage across the small condenser always has the value corresponding to the last echo time, so that meters placed in the plate circuit of a vacuum tube *L'* can be used for altitude indications. Since the change in grid voltage of this tube between soundings is just the change in the maximum voltage across the large condenser, the indications will show only the small variations caused by actual changes in altitude.

Flight tests of the Dubois-Laboureur Sonic Altimeter showed that the meter will operate properly from 6 meters to 300 meters when used over water. Over land the range was reduced by an amount depending upon the nature of the ground surface, but an echo was generally obtained at a greater altitude than 100 meters for any condition. Readings could be made with an uncertainty of 0.5 meter up to 20 meters, 1 meter between 20 and 50 meters, and 10 meters for higher altitudes. Figure 39 is a photograph of the indicator.

The actual sonic altimeter apparatus had a weight of 18 to 19 kilograms without the compressor, which added 4.5 kilograms. Weight of tubes, wiring, and fittings depended upon the particular installation.

Although the apparatus of Dubois and Laboureur de-

scribed above, is particularly interesting on account of the electrical chronoscope, a description of the CEEMA instrument made under their patents uses a magnetic-clutch chronoscope. This information is contained in an advertising pamphlet of Constructions Electro-Mécaniques d'Asnières of 236 Avenue d'Augenteuil, Asnières (Seine), France. Figure 40, taken from this source, shows the receiver at the left, and the siren emitter at the right. These units are apparently similar to those described in the literature. Figure 41 is a view of the amplifier and chronoscope circuit.

Figure 42 shows the front of the indicating unit. No diagram of the working parts is available but the operation is described as follows:

"The chronoscope is a small motor running at a rigorously constant speed which after reduction turns a shaft at the rate of one revolution in 1.4 seconds. This shaft carries an electromagnet which pulls down an armature when it is excited. This armature presses upon a heart-shaped cam which must then take a definite position with respect to the armature. On each revolution of the slow-turning shaft a contact is closed which causes the emission of the signal (this contact acts when the electromagnet passes by the zero point of the scale). When the echo is received the electromagnet and the armature have moved through a certain angle with respect to the moment of the emission. The excitation of the electromagnet by the echo pulls down the armature which strikes the cam. The cam then takes a definite position with respect to the armature.

"A hand rigidly connected to the cam indicates the angle moved through by the magnet between the emission of the signal and the echo, i.e., the height of the airplane with respect to the ground."

Figure 43 shows a typical installation of the Dubois-Laboureur sonic altimeter in a large airplane.

The weight of the CEEMA apparatus is given as 12.3 kilograms, exclusive of the air supply. This air supply must be capable of furnishing 20 liters per minute of free air at a pressure of about 10 atmospheres.

## Nandillon Sonic Altimeter

(References 11, 18)

M. A. Nandillon developed a sonic altimeter using electromagnetic units for both emission and reception with an oscillograph as the indicator, and applied for a French patent on the driving elements of the apparatus in 1928. Léglise (reference 18) notes that the investigation was carried out in secret and therefore the available information reveals only the general nature of the equipment.

Figure 44 shows one type of emitter used by Nandillon. A double diaphragm is formed of two disks 5 separated by a round central spacing and strengthening plate 11 through which the clamping screws 9 pass. This diaphragm is mounted on a backing chamber 3 by means of an annular clamp ring and screws. The chamber has cast reinforcing ribs for stiffness. Both the diaphragm and chamber are of light metal.

A vibromotor V, clamped to the center of the diaphragm by the screws 9, has two masses 7 and 10, which are connected together by elastic elements 6 so that the masses can move in a direction perpendicular to the diaphragm. The mass 10 is reinforced with fins  $n$  to prevent elastic deformations but is supported entirely from the diaphragm. Both masses carry laminated pole elements which serve as the magnetic circuit. The magnetic excitation is produced by windings placed on the pole pieces carried by mass 7. When the windings carry only an alternating current of frequency  $f$ , the corresponding magnetic flux produces an alternating force tending to pull the masses together twice each cycle of the current. When sufficiently large direct current is superimposed on the alternating current the magnetic flux is never reduced to zero and the frequency becomes  $f$  instead of  $2f$ .

Nandillon apparently relies on the inertia effect of the mass 10 to set the diaphragm into motion. From the description given it appears that the motion of mass 10 would be considerably greater than the more heavily loaded mass 7 below the lowest natural frequency of the system. The arrangement is a slightly damped vibrating system with 2° of freedom and will therefore display the complicated behavior characteristic of such a system if the forcing frequency is varied. No information is given as to the re-

lation between the operating frequency (3,500 cycles per second) and the natural frequencies of the various parts. The diagrams at the upper right of figure 44 are cited as showing the possibility of gaining directionality in the emitted signal by using a frequency which gives one nodal circle NN in the diaphragm. It is noted that the corresponding wave length is about half the diameter of the diaphragm for this case. This results in a small-size diaphragm for the emitter. However, in practice, the power available from a single unit is rather small for sonic altimeter purposes.

The diagram at the lower right of figure 44 shows the method of mounting the emitter in the surface of the wing 13 by means of a rubber ring 12. This arrangement eliminates the effect of parasite vibrations on the apparatus.

For his receiving element, Nandillon used a unit similar to the emitter but somewhat smaller. No mention is made of the frequency chosen or the provisions made for tuning the receiver to the signal frequency. Figure 45 shows a general circuit diagram of the Nandillon altimeter. The emitter already described is a transformer coupled to a vacuum-tube oscillator which is excited when a contact 26 is closed in the control timer and chronoscope. The signal is received and acts on the magnetic oscillograph element M.O. after passing through a vacuum-tube amplifier.

Details of the indicating chronoscope are shown in the diagram of figure 46. A constant-speed motor drives the shaft A through a gearshift 14 which makes it possible to vary the interval between soundings as the altitude changes. The gearshift is controlled by a shaft t which passes inside A and carries an index i for changing and indicating the setting of the interval.

The shaft A carries a rotating assembly S which supports the electromagnetic oscillograph M.O. and the illuminating system. A counterweight c is placed on the opposite side of S. As this assembly turns the motion is indicated by the rotation of the index I which is solidly connected to A. I is supported in the housing 19 which has a circular translucent scale 21.

The illuminating system is carried by the tube 17 and consists of a lens 16 which focuses the light of a small lamp 15 on a small hole 18 which acts as a bril-

liant point source. The moving element 22 of the magnetic oscillograph carries a shutter 20, which is normally interposed between the source and the translucent circle.

A projection 25 solidly connected to S sets off the sound signal when it momentarily closes the contact 26 on each one of its passages. 25 and 18 are located on the opposite ends of a diameter so that the light source is opposite the scale zero when the signal occurs.

An insulating drum 24 fitted with slip rings makes contact with the stationary brushes 23 and supplies the necessary electrical connections to the moving system.

When an echo reaches the receiver a pulse of current from the amplifier excites the oscillograph and moves the shutter 20. When the shutter is displaced a spot of light appears on the translucent scale opposite the altitude reading. It is noted that the length of the sound pulse decreases as the speed of the moving system is increased so that a proper compensation is automatically made to keep the same precision at all altitudes.

No tests of the Nandillon Sonic Altimeter are described and no weight information is given.

#### Jacquet-Badin Sonic Altimeter

(References 4, 11, 18, 25)

Jacquet and Badin have developed a sonic altimeter especially adapted for landing purposes. The emitter of their instrument sends out a train of sound waves which is automatically stopped when the first part of the echo reaches the receiver, remains silent as long as the receiver is excited, and begins a new signal when the last of the returning wave train is past. This action results in 100-percent modulation of a continuous wave at a frequency of modulation which depends upon the altitude. A meter designed to measure this modulation frequency acts as the indicating unit.

Figure 47 is a photograph of the Jacquet-Badin Sonic Altimeter. The left-hand unit contains the electromagnetic emitter and the electromagnetic-microphone receiver;

the frequency meter indicator is in the middle; the oscillator and amplifier unit is at the right. The outfit is entirely electrical and can be operated from the usual airplane battery power supply.

A cross section of the emitter and receiver unit is shown in figure 48. M is a powerful electromagnetic driving unit which feeds into an exponential horn made of acoustic insulating material. The electromagnetic microphone m is connected to an exponential horn lined with sound-absorbing material which acts as an acoustic filter. The entire assembly is carried by a supporting member S. The receiving horn can be moved parallel to its axis in order to find the best position for reducing direct transfer of the signal to the receiver.

The frequency meter circuit proposed by Jacquet and Badin is shown in figure 49. The relay R is connected to the emitter in such a manner that the contacts C' are closed during each period of silence. When C' is closed, current from the battery p flows in the resistance r and charges the condenser  $\gamma$  through the full wave copper-oxide rectifier S and a large condenser  $\Gamma$ .  $\Gamma$  is always charged in the same direction on account of the rectifier action. A high resistance voltmeter V placed across  $\Gamma$  measures the average potential. It is stated that the reading will be a function of frequency. However, the arrangement is similar to the ordinary rectifier type of A.C. voltmeter, which is characterized by a response independent of frequency over a wide range, so it is questionable whether the circuit given will fulfill its supposed function without modifications.

The Jacquet-Badin Altimeter has a weight of 9 kilograms, and is graduated up to 20 meters altitude. No data on actual flight tests have been given.

#### Delsasso Sonic Altimeter

(References 4, 10, 26)

Delsasso of the University of California and the California Institute of Technology reported in 1934 the results of a sonic-altimeter investigation. He produced an experimental instrument which was tested both on the ground and in flights with the Goodyear airship "Volunteer".

This instrument uses a mechanically excited diaphragm with a special coupling horn as the source of sound. The receiver is a diaphragm tuned to the emitter frequency which causes a flash in a rotating neon discharge tube when set in motion by the echo.

Figure 50 is a diagram of the sound emitter. The diaphragm is machined from a solid steel ring to have a natural frequency of 2,000 cycles per second. The signal is produced by a blow from the clapper C which occurs when current through the electromagnet E is broken. Energy is efficiently transferred to the air through the coupling elements shown. (Delsasso notes that the design is similar to that used in the Bostwick loudspeaker.) Each signal has a duration of about 0.02 of a second.

Details of the receiver are shown in figure 51. A duralumin diaphragm D, 0.001 inch thick and tuned to 2,000 cycles per second, carries a small platinum contact button at its mid-point. A second contact is pressed against the first by the light platinum spring S. This spring is tuned to a natural frequency of about 95 cycles per second. A tube R contains a hygroscopic material which serves to keep the closed chamber above the diaphragm dry. The nut M is used to make the proper adjustment of the spring contact. The spring will follow the diaphragm for all low frequency sounds, but even a weak sound with the natural frequency of the diaphragm will produce such high accelerations that the contact is broken once each cycle of the motion. This arrangement gives a very effective filtering action for parasite noises.

The Delsasso chronoscope uses a neon discharge tube as the indicating element. The essential parts of the chronoscope are indicated in figure 52. The neon tube P is carried by a disk which is rotated at constant speed by an electric motor. A circular scale D just outside the path of the neon tube is graduated directly in altitude. A cam and contact arrangement C is adjusted to release the striker of the sending diaphragm at the instant the neon tube passes the zero scale graduation. When the echo returns the diaphragm T is set in motion and contact is broken with N. This action removes a short circuit from the circuit containing the battery E and the resistance R and allows the voltage E to overcome the grid bias battery,  $E_g$ . The grid of the vacuum tube is made sufficiently positive to cause a discharge in the neon lamp. Altitude is estimated by observing the scale position of the lamp when it first starts to glow.

Delsasso's experimental installation is shown in figure 53. The receiver is mounted at the front of the gondola and the sending unit at the rear. In operation the contact spring of the receiver was adjusted until the neon lamp just failed to flicker under the airship's noise alone.

During a series of flight tests, it was found possible to measure altitudes between 4 feet and 350 feet. A stronger source of sound gave results up to 700 feet. No data on the weight of the apparatus were given. This is unimportant since the equipment was designed to investigate the sonic altimeter problem rather than to produce a service instrument.

### Echoscope

(References 27, <sup>28</sup>33)

Electroacoustic G.m.b.H. of Kiel, manufactures a sonic altimeter known as the ECHOSCOPE. This instrument was successfully used on the German airship "Hindenburg" and will be installed on the new airship LZ 130.

The ECHOSCOPE uses a compressed-air siren as the source of sound and an electromagnetic microphone as the sensitive element of the receiver. The indications are shown as deflections of a mechanical pointer on a dial of conventional aircraft-instrument size. A great improvement in operation over the explosion-type emitter is achieved by selecting a siren frequency well removed from the parasitic noises of the airplanes. With all the sound energy in a single frequency, it is comparatively easy to make a microphone and filter system sensitive to the echo but which will suppress extraneous sounds. The advantages of an almost continuously reading mechanical indicator are obvious.

Figure 54 shows the essential parts of the ECHOSCOPE. The indicator 1 is connected through the central switch 3 to a 12-volt direct-current supply at 2. The siren 4 is supplied with air from the high-pressure tank 7. A reducing valve 6 holds the siren supply between 4 and 8 atmospheres. When the apparatus is not in use the valve 8 is closed to prevent leakage. The tuned electromagnetic microphone receiver 9 is connected to the indicator through the amplifier 11. Figures 55 and 56 show the external appearance of the emitter and receiver, respectively.

Figure 57 is a diagram showing the essential parts of the ECHOSCOPE indicating system. A constant-speed electric motor 13 drives the shaft 3 through gears 11 and 12. This shaft carries an electromagnet 2 which is operated by current from the slip rings 8 and 9. A second electromagnet 1 is similar to 2 except that it does not rotate. The circular disk armature 4 is connected rigidly to the pointer 5 which moves over the altitude scale when 4 rotates; the pointer and disk assembly is free to move axially between the two circular electromagnets. When the disk is held by excitation of the electromagnet 1 the pointer will be stationary. If the supply to 1 is broken while 2 is excited, the disk will jump over to the rotating system and the pointer will move over the scale. The various parts are so designed that no appreciable slipping occurs when the disk is in contact with either magnet. There is also an arrangement which returns the pointer to zero after a sounding.

A sounding is started when the constant-speed siren motor opens a valve and admits air to produce a pulse of sound. At the same instant the starting contacts 6 and 7 are opened so that the electromagnet 1 releases the disk 4 which is instantly pulled over to the other magnet and starts to rotate. This results in a uniform motion of the pointer over the graduated altitude scale until the receiver picks up the echo and feeds a corresponding alternating-current pulse into the amplifier. In the amplifier this pulse is rectified and magnified until it is able to operate a relay which momentarily breaks the contacts 7 and 8. This action interrupts the current supply to the rotating magnet 2 and permits the disk 4 to move back to the stationary magnet 1, thus stopping the pointer at a scale reading corresponding to the proper altitude.

The pointer holds this position until just before another sounding, when it is automatically returned to zero.

As shown in figure 58, two scales are provided for the instrument: one for altitudes up to 100 meters, and a second, for altitudes up to 500 meters. The necessary shift in the gear ratio within the instrument is made by changing the position of the control knob. When the low-range scale is in use, soundings are made automatically at 1.5-second intervals while for the higher range this interval is increased to 7.5 seconds.

The total weight of the ECHOSCOPE is 14.8 kilograms with an additional 13 kilograms for a compressed-air bottle. This air supply is capable of making 200 to 250 soundings on the low-range scale and about one-half of this number on the high-range scale.

The manufacturers of the ECHOSCOPE report that the instrument will give reliable results up to 1,000 feet altitude under favorable conditions and will continue to indicate until the landing gear is just above the ground. Above forests the maximum useful altitude is reduced to about 500 feet. At greater altitudes useful information can still be obtained from the instrument by the use of a pair of earphones connected to the amplifier and worn by an observer who notes the position of the pointer when the echo reaches the receiver. When the indicator is used altitude readings are uncertain by about 1 foot.

## APPENDIX B

### EQUATIONS OF SOUND PROPAGATION

Sound theory deals with the propagation of pressure waves through an elastic medium. The simplest and most useful form deals with plane waves, i.e., disturbances which vary only with time and distance along a single direction, which will be denoted as the  $x$ -axis. Three conditions must be fulfilled at each instant by the particles in a slice  $dx$  thick, which has its equilibrium at some position  $x$  along the axis (reference 32).

- (1) The force due to the instantaneous pressure difference between the faces of a unit area of the slice will be balanced by the inertia reaction of material in the slice.
- (2) The equation of continuity must be fulfilled, i.e., the material within the slice under equilibrium conditions will remain within the slice during any change which may occur.
- (3) The relation between pressure and density will obey the equation for an adiabatic change in a perfect gas. This is based upon the experimental fact that fluctuations in a sound wave are so rapid that heat transfer between adjacent layers can be neglected.

Equating the pressure differential force across the unit area of the slice which is  $dx$  thick at equilibrium, gives:

$$\rho \frac{\partial^2 \xi}{\partial t^2} = - \frac{\partial P}{\partial x} \quad (28)$$

The equation of continuity is

$$\rho \left( 1 + \frac{\partial \xi}{\partial x} \right) = \rho_0 \quad (29)$$

The adiabatic relation between pressure and density is

$$\frac{P}{P_0} = \left( \frac{\rho}{\rho_0} \right)^\gamma \quad (30)$$

where  $\rho$  is instantaneous density

$\rho_0$ , density at equilibrium.

$P$ , instantaneous pressure

$P_0$ , pressure at equilibrium.

$\xi$ , displacement from equilibrium

$x$ , distance along the normal to the plane wave

$\gamma = \frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}$

Differentiating the equation of continuity with respect to  $x$  and substituting  $\frac{\partial \rho}{\partial P} \frac{\partial P}{\partial x}$  for  $\frac{\partial \rho}{\partial x}$  gives

$$\frac{\partial^2 \xi}{\partial t^2} = - \left( \frac{\rho}{\rho_0} \right)^2 \left( \frac{\partial P}{\partial \rho} \right) \frac{\partial^2 \xi}{\partial x^2} \quad (31)$$

Substituting the value of  $\frac{\partial P}{\partial \rho}$  obtained by differentiating the adiabatic relation gives

$$\frac{\partial^2 \xi}{\partial t^2} = \frac{\gamma P}{\rho} \left( \frac{\rho}{\rho_0} \right)^2 \frac{\partial^2 \xi}{\partial x^2} \quad (32)$$

Now if the changes in pressure and density are small compared to these quantities themselves  $\left(\frac{\rho}{\rho_0}\right)^2$  can be taken as unity while equilibrium values can be used in  $P/\rho$  so that

$$\frac{\partial^2 \xi}{\partial t^2} = c^2 \frac{\partial^2 \xi}{\partial x^2} \quad (33)$$

where  $c^2 = \frac{\gamma P_0}{\rho_0} = \text{constant}$

Equation (33) is the well-known wave equation which expresses the condition that a disturbance is propagated without change of form at the constant velocity  $c$  (reference 32). When the assumption of fluctuations with a negligibly small effect on the coefficient of  $\frac{\partial^2 \xi}{\partial x^2}$  is not fulfilled, the velocity varies with the intensity of the disturbance. Practically, this means that for disturbances which are too intense the form changes as the wave is propagated. Such a wave starting with a simple sinusoidal form will be altered by the appearance of higher harmonics as it moves through the medium.

In sound work it is customary to work with the instantaneous difference between the actual pressure  $P$  and the equilibrium pressure  $P_0$ . This difference is called the excess pressure or the sound pressure and is denoted by  $p_i$ . For a sinusoidal wave form the wave equation gives for instantaneous displacements and excess pressures (reference 32):

$$\xi = \xi_m \sin 2\pi \left( \frac{x}{\lambda} - \frac{t}{T} \right) \quad (34)$$

$$p_i = - \xi_m \rho_0 c \omega \cos 2\pi \left( \frac{x}{\lambda} - \frac{t}{T} \right) \quad (35)$$

where  $\xi_m$  is amplitude of particle displacement,  
 $\lambda$ , wave length,  
 $T$ , period

$n$ , frequency,

$\omega$ ,  $2\pi n$

The particle acceleration at any point can be found by differentiating equation (34) twice with respect to time to obtain

$$\frac{\partial^2 \xi}{\partial t^2} = \xi_m \omega^2 \sin 2\pi \left( \frac{x}{\lambda} - \frac{t}{T} \right) \quad (36)$$

#### RELATION BETWEEN INTENSITY AND EXCESS PRESSURE

By definition the intensity of sound in a plane wave is equal to the average rate at which energy is transferred across a unit area of the wave front. This is equal to the sound-pressure force acting on the unit area multiplied by the particle velocity and averaged over a complete cycle, i.e.:

$$I = \frac{1}{T} \int_0^T p_i \left( \frac{\partial \xi}{\partial t} \right) dt = \frac{1}{T} \int_0^T p_o c^2 \frac{\partial \xi}{\partial x} \frac{\partial \xi}{\partial t} dt \quad (37)$$

which gives

$$I = \frac{p_{im}}{2\rho_o c} = \frac{p}{\rho_o c} \quad (38)$$

where  $p_{im}$  is the amplitude of sound pressure

$p$ , root mean square value of sound pressure

Sound pressure is customarily measured in dynes per square centimeter. For convenience, a unit called the bar is defined as 1 dyne per square centimeter. Intensity is denoted by the symbol  $I$  and measured in watts per square centimeter. The product  $\rho_o c$  is usually calculated for  $P = 760$  millimeters of mercury and a temperature of  $20^\circ \text{C}$ ., which gives a numerical value of 42 in c.g.s. units. For this case the relation between intensity and root mean square sound pressure is

$$I = \frac{p^2}{42 \times 10^7} \text{ watts per square centimeter} \quad (39)$$

It is convenient to compare intensities in terms of the logarithmic units called decibels and denoted as db. By definition, the difference between two intensities  $I_1$  and  $I_2$  is:

$$\text{Difference in db} = 10 \log_{10} \frac{I_1}{I_2} \quad (40)$$

In general, the intensity of sound at a distance from a sound source of  $W$  watts will depend upon the area over which the sound energy is distributed and the amount of absorption in the sound path. In sonic altimeter work, the only important case is that in which the sound energy is confined to a more or less definite solid angle. If this solid angle is  $\Omega$  the area for any distance  $R$  at which the source can be considered as a point becomes

$$\text{Area} = \Omega R^2 \quad (41)$$

For a cone of half angle  $\Delta$  the area at  $R$  becomes

$$\text{Area} = 2\pi R^2 (1 - \cos \Delta) \quad (42)$$

It follows that the intensity at  $R$  from a source of  $W$  watts into a cone is

$$I = \frac{W}{2\pi R^2 (1 - \cos \Delta)} \quad (43)$$

In terms of  $W$  and  $R$  the sound pressure becomes

$$p = \sqrt{\frac{\rho_0 c W 10^7}{2\pi R^2 (1 - \cos \Delta)}} \quad (44)$$

where

$p$  is in bars.

$W$  is in watts.

$R$  is in centimeters.

If specular reflection at the ground is assumed, the relation between the echo path  $R_e$  and the actual altitude  $h_a$ , when the cone angle is inclined at an angle  $\delta$  away

from the vertical, is (see fig. 15):

$$R_e = \frac{2h_a}{\cos \delta} \quad (45)$$

so that

$$p = \sqrt{\frac{\rho_o c W 10^7 \cos^2 \delta}{8\pi h_a^2 (1 - \cos \delta)}} \quad (46)$$

If  $h_a$  is expressed in feet and  $\rho_o c$  is taken as 42, equation (46) becomes

$$p = 134 \frac{\cos \delta}{h_a} \sqrt{\frac{W}{1 - \cos \delta}} \quad (47)$$

#### APPENDIX C

##### REFLECTION AT THE GROUND SURFACE

Two limiting cases of reflection at the ground can exist. In specular reflection the sound is reflected with, the angle of reflection equal to the angle of incidence and the energy always confined within the same cone angle. In diffuse reflection (reference 13), Lambert's Law is assumed to hold for sound as in the case of optics, i.e.:

$$I_R = I_{R_0} \cos \beta \quad (48)$$

in which it is assumed that the sound, incident normally on the reflecting surface, is reflected back with intensity  $I_{R_0}$  at distance  $R_0$  from the ground along the normal, and with intensity  $I_R$  at the same distance along a path making an angle  $\beta$  with the normal.

If the incident sound has intensity  $I_D$  where the cone of radiation cuts out an area  $A$  on the ground, the total incident power is  $I_D A$ , and the total reflected power is  $K I_D A$ , where  $K$  is the reflection coefficient of the ground surface. The total reflected power must also be equal to the integral of the right-hand member of

equation (48) over a hemisphere. That is,

$$\begin{aligned} KI_D A &= \int_0^{\pi/2} (I_{R_0} \cos \beta) 2\pi R \sin \beta R d\beta \\ &= \pi R^2 I_{R_0} \end{aligned} \quad (49)$$

$$\text{or} \quad I_{R_0} = KI_D A / (\pi R^2) \quad (50)$$

$$\text{and} \quad I_R = \frac{KI_D A}{\pi R^2} \cos \beta \quad (51)$$

If the aircraft is a distance  $D$  above the ground, and if  $\Delta$  is the half angle of the radiation cone, we have  $A = \pi (D \tan \Delta)^2$ . If, moreover, the velocity of the plane is small compared with the velocity of sound in air, the portion of the sound reflected back to the plane corresponds to a very small value of  $\beta$ , and it is a good approximation to put  $\cos \beta = 1$ . Then, with the above value of  $A$ , equation (51) yields for the intensity at the plane, considering that at the plane  $R = D$ ,

$$I_R = K I_D \tan^2 \Delta \quad (52)$$

For specular reflection from a surface with reflection coefficient  $K'$ , the intensity at the plane is

$$I_R' = K' \left( \frac{D}{2D} \right)^2 I_D = \frac{1}{4} K' I_D \quad (53)$$

Hence the ratio of intensities at the plane for the two extreme cases is:

$$\frac{I_R'}{I_R} = \frac{K'}{4K \tan^2 \Delta} \quad (54)$$

## APPENDIX D

## RADIATION OF SOUND FROM A VIBRATING DISK

A vibrating disk set in an infinite plane baffle will radiate sound with directionality depending on the dimensions of the disk and the frequency of its vibrations. If the frequency  $n$  corresponds to a wave length  $\lambda$  of sound in air, and if  $a$  is the radius of the disk, the distribution of intensity in front of the baffle will be as plotted in figures 17 and 18 for several values of  $\lambda/a$ .

The mathematical basis for the curves of figures 17 and 18 will be briefly stated (reference 32). Consider the surface  $S$  of the disk to be composed of elements  $dS$ . Let the distance from an arbitrary point  $N$  in front of the baffle to an arbitrary surface element  $dS$  be called  $h$ . Let  $r$  be the distance from  $N$  to the center of the disk, and let  $\theta$  be the angle between the line or  $r$  and the normal to the center of the disk.

Then the element  $dp_i$  of sound pressure at point  $N$  due to the simple source  $dS$  is

$$dp_i = i \left( \frac{\rho_0 n u_m dS}{h} \right) e^{2\pi i \left( \frac{h}{\lambda} - \frac{t}{T} \right)} \quad (55)$$

where  $u_m$  is the velocity amplitude of the vibration.

If  $N$  is far from the disk, so that  $h$  is nearly equal to  $r$ , it is a close approximation to put

$$p_i = \int dp_i = i \frac{\rho_0 n u_m}{r} \int e^{2\pi i \left( \frac{h}{\lambda} - \frac{t}{T} \right)} dS \quad (56)$$

Integration gives

$$p_i = \pi i n \rho_0 u_m a^2 \frac{e^{2\pi i \left( \frac{r}{\lambda} - \frac{t}{T} \right)}}{r} \left[ \frac{2J_1 \frac{2\pi a}{\lambda} \sin \theta}{\frac{2\pi a}{\lambda} \sin \theta} \right] \quad (57)$$

Since at large distances the particle velocity is

$\frac{p_1}{\rho_0 c}$  the intensity distribution in terms of the angle  $\theta$  takes the form:

$$I = \frac{1}{8\pi} \rho_0 c u_m^2 \left( \frac{2\pi a}{\lambda} \right)^2 \left[ \frac{2J_1 \left( \frac{2\pi n}{\lambda} \sin \theta \right)}{\frac{2\pi a}{\lambda} \sin \theta} \right]^2 \quad (58)$$

It is from this equation that the curves of figures 17 and 18 are drawn.

The function  $[2J_1(x)/x]$  has the property of being unity for  $x = 0$  and remaining nearly unity until  $x = \frac{1}{2} \pi$ . Therefore, as long as  $\lambda > 2\pi a$ , the intensity distribution is nearly independent of  $\theta$ . As the wave length becomes smaller than the circumference of the disk, the energy is concentrated more and more along the axis, as shown in figure 18. For such values of  $\lambda$ , the curves actually have small subsidiary lobes, but these have not been included in the figures, since they are not important in the sonic altimeter problem.

If  $W$  is the total power radiated from the disk, the expression for  $W$  (reference 54) is:

$$W = \frac{(\rho_0 c) (\pi a^2) (2\pi n X_0)^2}{2} \left[ 1 - \frac{J_1 \left( \frac{4\pi a}{\lambda} \right)}{\frac{2\pi a}{\lambda}} \right] \quad (59)$$

where  $X_0$  is the r.m.s. value of the displacement of the disk.

For low frequencies such that  $\frac{\lambda}{a} > 12$ , equation (59) approaches the form

$$W = \frac{\rho_0 \pi a^4 (4\pi^2 n^2 X_0)^2}{4c} \quad (60)$$

For high frequencies such that  $\frac{\lambda}{a} < 3$ , the bracketed expression in equation (59) approaches unity, so that  $W$  is closely represented by

$$W = \frac{\rho_0 c \pi a^2 (2\pi n X_0)^2}{2} \quad (61)$$

If  $W$  is in watts and all other quantities in c.g.s. units, equations (60) and (61) become

$$W = (4.64 \times 10^{-11}) a^4 n^4 X_0^2 \text{ watts} \quad (62)$$

and

$$W = (2.62 \times 10^{-3}) a^2 n^2 X_0^2 \text{ watts} \quad (63)$$

The latter equation corresponds, at a frequency of 3,000 cycles per second, to a maximum displacement

$$x_{\max} = \frac{0.0203}{a} \text{ centimeters per radiated watt} \quad (64)$$

#### APPENDIX E

##### VARIATION OF INTENSITY WITH PULSE LENGTH

The theoretical concept of purely monochromatic radiation (radiation of a single wave length) cannot be realized in practice because it represents an infinitely long wave train. The starting and stopping of the vibration involves a spread of frequency inversely proportional to the length of the pulse (reference 32).

In general, if the sound pressure is an arbitrary function of the time, the Fourier integral representation is

$$p_i(t) = \int_{-\alpha}^{\alpha} p(n) e^{2\pi i n t} dn \quad (65)$$

The component of the wave having frequency  $n$  has the pressure amplitude equal to  $p_o(n) = p(n) = p(-n)$ .

Applying these relations to the "pulse function":

$$p_i(t) = \begin{cases} 0 & \text{for } t < -\frac{t_0}{2} \\ p_m \cos(2\pi n_0 t) & \text{for } -\frac{t_0}{2} < t < \frac{t_0}{2} \\ 0 & \text{for } t > \frac{t_0}{2} \end{cases} \quad (66)$$

one obtains this distribution in frequency:

$$p_o(n) = 2p_m \frac{\sin [\pi (n_o - n) t_o]}{n - n_o} \quad (67)$$

If the pulse contains  $m$  cycles of the wave of frequency  $n_o$ , we may put  $t_o = m/n_o$ . With the further notation,  $v = n/n_o$ , the intensity distribution becomes:

$$I(n) = \frac{2p_m^2}{\rho_o c n_o^2} \left[ \frac{\sin n \pi (1 - v)}{1 - v} \right]^2 \quad (68)$$

Or, calling  $I_o = \frac{p_m^2}{2\rho_o c}$ , the intensity of the steady state, we have:

$$\frac{I(n)}{I_o} = \frac{4}{n_o^2} \left[ \frac{\sin m \pi (1 - v)}{1 - v} \right]^2 \quad (69)$$

This ratio is plotted as a function of  $v$  in figure 19, in which only the large central lobes of the curves are displayed.

## CONCLUSIONS

## CONCLUSIONS BASED ON THE LITERATURE

1) A number of sonic altimeters have been constructed which operated satisfactorily up to a maximum altitude of approximately 800 feet under airplane cruising conditions.

2) For gliding flight in airplanes, the maximum operating altitude will be approximately double that for cruising conditions. In lighter-than-air craft the maximum will be about three times the limit for airplanes.

3) With a properly designed instrument, altitude readings can be carried down to approximately 10 feet above the ground.

4) Five distinct sonic altimeter developments have produced commercial instruments. A list is given on pages 88-89, with information on prices and manufacturers.

5) The best of these commercial instruments will have an installation weight of about 60 pounds. The maximum useful altitude will be approximately 15 feet per pound of weight.

6) The results actually obtained justify an investigation into the value of the sonic altimeter as an aircraft instrument in modern practice.

7) One of the present-day commercial sonic altimeters would be suitable for the experimental work.

8) In case of a decision favorable to the sonic altimeter, a continuation project could be directed toward improving the instrument on the basis of findings from the previous tests.

## THEORETICAL CONCLUSIONS

1) The lowest operating altitude of a sonic altimeter is determined by the length of the sound signal and the ability of the chronoscope to measure short-time intervals.

2) The maximum operating altitude of a sonic altimeter is determined by the ability of the receiving system to distinguish the echo from noises due to the aircraft.

3) Except at very low altitudes, errors due to timing and to separation of the sending and receiving systems are negligible.

4) Errors due to humidity and temperature effects on sound velocity are negligible except in extreme conditions.

5) Errors due to aircraft velocity can be neglected except at very high speeds.

6) Errors due to inclination of the flight path with respect to the ground can be neglected except in extreme cases.

7) Inclination of the flight path with respect to the ground produces a difference between the received frequency and the emitted frequency due to the Doppler Effect.

8) Excessive sound intensities produced by the emitter will be subject to abnormal attenuation due to nonlinearity of air as an elastic medium.

9) A sonic altimeter signal decreases in intensity inversely as the square of echo-path length due to spreading of the energy.

10) Attenuation due to friction in the atmosphere increases rapidly with frequency. For a frequency of 3,000 cycles per second the attenuation is about  $\frac{1}{2}$  db per hundred feet of path length.

11) Atmospheric disturbances are accompanied by erratic attenuation effects of large magnitude. Quantitative data are lacking on losses of this type.

12) Losses due to diffuse reflection and absorption at the ground vary from zero for smooth ice to about 85 percent for forests.

13) Sources of sound which use diaphragms as the element for converting electrical or mechanical energy into sound energy are suitable for low-power emitters but are handicapped by the excessive accelerations required for high outputs.

14) The directional properties of a diaphragm transmitter can be predicted approximately by theory but the results actually obtained in a given case must be determined by experiment. Efficient use of sound power in a sonic altimeter requires that the source be designed to direct the beam toward the receiver position when the echo is received.

15) For short pulses of sound at a constant frequency, the amount of energy effective at the receiver in the original pulse frequency depends upon the number of cycles in the pulse. A minimum number of cycles between 15 and 30 is required to produce a good concentration of the echo energy at the frequency of the emitter.

16) All types of standard microphones are much more sensitive than necessary to detect the sonic altimeter echo if aircraft noise were absent. A rugged microphone adapted to work with a filter system is best suited to the sonic altimeter problem.

17) Since the limiting factor in sonic altimeter performance is the signal intensity required to bring the echo above the noise level due to the airplane, the use of a well-designed filter system to eliminate aircraft interference is necessary.

18) The table below gives the estimated maximum altitudes obtainable in an airplane at cruising speed under the best and worst atmospheric and ground conditions. The calculations are based on assumptions consistent with experimental values of sound pressure required at the airplane and the known data on absorption losses.

Maximum altitude (best conditions)	Power	Maximum altitude (worst conditions)	Best altitude Worst altitude
<u>feet</u>	<u>watts</u>	<u>feet</u>	
500	10	175	2.9
650	25	225	2.9
780	50	265	2.9
935	100	300	3.1
1025	150	330	3.1
1300	500	410	3.2

19) The table shows that there is a factor of about 3 to 1 between the maximum altitude obtainable under best and worst operating conditions.

20) Comparison of values from the table with altitudes found experimentally shows that the instruments which have been constructed achieve almost the theoretical maximum performance.

21) The gain in maximum operating altitude for a given increase in power falls off rapidly for outputs over 100 watts. This fact suggests the existence of an economic limit to the range of a practical sonic altimeter.

22) The performance of sonic altimeters can be improved by reducing the interference effect of aircraft noise.

#### RECOMMENDATIONS

Two points should be investigated in connection with the sonic altimeter problem.

- I) Will a sonic altimeter installed in a modern airplane be sufficiently useful to justify its weight and complication?
- II) Is it possible to improve sonic altimeter performance on modern airplanes by the use of more selective receiving systems?

It is recommended that the first question be investigated by the procedure outlined on page 22 of this report. The principal features of the suggested project are:

- 1) Purchase of a commercial sonic altimeter.
- 2) Quantitative investigation of the performance of this instrument.
- 3) During these tests two types of data should be accumulated.
  - a) Reactions of a pilot "under the hood" to the usefulness of a sonic altimeter in various flight situations.

- b) Quantitative records (preferably oscillographic) of variations in echo intensity with atmospheric conditions, terrain, and altitude.
- 4) A report giving results from the preceding investigation and containing recommendations to continue or abandon sonic altimeter work.

The second general question should be investigated by studies of the noise spectrum on representative modern airplanes. In this work it would be desirable to use installations at various locations on the airplane which simulate actual sonic altimeter conditions.

As an additional project of great value to sonic altimeter design, it is recommended that a systematic investigation of sound attenuation due to disturbances in the free atmosphere be carried out. This work should be coordinated with meteorological data. It would be desirable to outline the project and carry out the work with the cooperation of some organization interested in meteorology.

#### COMMERCIALLY AVAILABLE SONIC ALTIMETERS

BEHMLLOT - Manufacturer: Behm-Echolot-Fabrik, Hardenbergstrasse 31, Kiel, Germany. Price: RM 4,500 for type L XI, at Kiel, exclusive of duty. Reference: Letter from Behm-Echolot-Fabrik and advertising reprint from Zeitschrift Deutsche Technik, August 1935 - Behmlot zur Höhenmessung im Flugzeug.

RICE-GENERAL ELECTRIC- Manufacturer: General Electric Co., 1 River Rd., Schenectady, New York. No price given. Service installations to date have been on airships only; test installations on Army airplanes. Reference: Letter from G. E. and advertising pamphlet - Sonic Altimeter for Aircraft.

FLORISSON-SCAM - Manufacturer: Société de Condensation et d'Applications Mécaniques, 42 Rue de Clichy, Paris, France. Price: 15,400-22,000 francs. Delivery: 4 months. Reference: Letter from SCAM and advertising extract from La Nature, February 1, 1933 - Une Nouvelle Sonde pour Avions.

DUBOIS-LABOUREUR-CEMA - Manufacturer: Constructions Electro-Mécaniques d'Asnières, 236 Avenue d'Argenteuil Asnières (Seine), France. Price: 150 livres sterling. Reference: Letter from CEMA and advertising pamphlet - Le Sondeur Acoustique Aérien.

ECHOSCOPE - Manufacturer: Electroacoustic G.m.b.H., Kiel, Germany. Price: RM 5,100, delivered in Berlin. Delivery: 6 months. Reference: Letter from Electroacoustic and advertising pamphlet - Echoscope.

#### NOTATION

(No attempt is made to include in this list, symbols used to mark geometrical figures or to describe apparatus.)

##### Symbol

$v$	velocity of aircraft.
$v_0$	calibration velocity of aircraft.
$t$	time (in particular, time between signal and echo).
$d$	distance (between sender and receiver).
$c$	velocity of sound in air.
$c_0$	calibration velocity of sound in air.
$\Delta t$	timing error.
$h_a$	actual altitude of aircraft.
$h_i$	indicated altitude of aircraft.
$\gamma$	ratio of specific heat at constant pressure to specific heat at constant volume.
$R_g$	universal gas constant.
$T$	absolute temperature; period of vibration.
$m$	molecular weight; as subscript, denoting maximum values.
$C$	Centigrade temperature.

Symbol

$F$	Fahrenheit temperature.
$\sigma$	$v/c$ .
$\sigma_0$	$v_0/c_0$ .
$\lambda_s$	wave length from stationary source.
$\lambda_0$	wave length from moving source as observed by stationary observer.
$n_0$	$c/\lambda_0$ = frequency of moving source as observed by stationary observer; frequency of steady state component of sound pulse.
$n_s$	frequency of source.
$n_R$	frequency received on aircraft.
$\eta$	$(n_R)/(n_s)$ .
$\alpha$	angle between flight path and reflecting surface.
$\rho$	instantaneous density.
$P$	instantaneous pressure.
$\rho_0$	density at equilibrium.
$P_0$	pressure at equilibrium.
$\xi$	displacement of air from equilibrium.
$P_i$	$P - P_0$ = instantaneous sound pressure.
$\lambda$	wave length.
$n$	frequency.
$w$	$2\pi n$
$I$	intensity of radiation (energy/area/time).
$p$	r.m.s. value of $p_i$ .
$W$	power.

Symbol

$\Omega$	solid angle.
$I_{R_0}$	intensity of reflected sound at distance $R_0$ normal to ground.
$I_R$	intensity of reflected sound at distance $R$ at angle $\beta$ to ground.
$I_D$	intensity of incident sound at ground.
$D$	distance from aircraft to ground.
$\Delta$	half angle of radiation cone.
$K$	reflection coefficient for diffuse reflection.
$K'$	reflection coefficient for specular reflection.
$a$	radius of vibrating disk.
$u_m$	velocity amplitude of vibrating disk.
$X_0$	r.m.s. displacement of vibrating disk.
$t_0$	length of sound pulse.
$n$	number of cycles in pulse.
$I_0$	intensity of steady state component of pulse.
$v$	$n/n_0$ = ratio of frequency of partial component to frequency of steady state component of pulse.
hz	cycles per second.

*u*  
*1/2* *absorption*  
Massachusetts Institute of Technology,  
Cambridge, Massachusetts, July 8, 1937.

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Plate I  
SUMMARY OF SONIC ALTIMETER DEVELOPMENTS

Name	Date	References	Source of Sound	Power Supply	Frequency, Duration, and Interval of Signals	Echo Receiver
Behm (BEHMLOT)	1924-	1,2,3,4,6,6,7, 8,9,10,11,18	Pistol (Experimental: mechani- cally excited diaphragm)	Blank cartridges. (Experimental: electro- mechanical)	Frequency: wide range Duration: -- Interval: 3 sec.	Carbon microphone and horn.
Mandillon	1928-	11,18	Armature-excited directive diaphragm without horn.	Electrical power supply of airplane.	Frequency: 3500 Hz. Duration: variable (order of 0.005 sec.) Interval: manually variable with alt.	Electromagnetic micro- phone
Rice (General Electric)	1929-31	4,10,11,13,14, 16	Whistle and megaphone (Experimental: diaphragm)	Compressed gas bled from engine cylinder and stored in tank at 50-100 lbs./sq. in. (Experimental: electric)	Frequency: 3000 Hz. Duration: 0.01 sec. Interval: 2 sec.	Stethoscope ear-pieces, acoustic filter, and megaphone.
Florisson (SOAM)	1931-	4,11,16,17,18	Whistle and conical horn.	Compressed air at 6-8 atmospheres.	Frequency: -- Duration: 0.05 sec. Interval: 1.5 sec.	Stethoscope ear-pieces, acoustic filter, and parabolic horn. (Experimental: electric filter and amplifier)
Dubois Laboureur (CEMA)	1932-	4,11,18,19,20, 21,22,23,24	Siren and megaphone. (Original: locomotive whistle) (Experimental: mechanically excited diaphragm)	Compressed air. Requires 20 liters per minute of free air at 10 atmos- pheres.	Frequency: 1500 Hz. Duration: 0.015 sec. Interval: 0.7 sec. at low alt. 2.0 sec. at high alt.	Tuned electromagnetic microphone, amplifier, band-pass filter, and megaphone.
Jacquet Badin	1932-	4,11,16,25	Electromagnetically excited diaphragm and exponential horn.	Electrical power supply of airplane.	Frequency: 2000 Hz. Duration: continuous; automatic 100% modula- tion. Interval: = duration of signal.	Electromagnetic micro- phone, amplifier, acoustic and electric filters, and exponential horn.
Delessio	1934	4,10,26	Mechanically excited diaphragm and Bostwick- type coupler.	Electrical.	Frequency: 2000 Hz. Duration: 0.02 sec. Interval: --	Electrical contact on resonant diaphragm filter, and megaphone.
Stethoscope	Before 1936-	27,28	Siren and parabolic horn.	Compressed air from high pressure storage tank, reduced to 4 - 8 atms. by valve.	Frequency: 1800 Hz. Duration: 0.011 sec. Interval: 1.5 sec. at low alt. 7.5 sec. at high alt.	Tuned electromagnetic microphone, amplifier and exponential horn.
Henry Hughes and Son	1934-	20,31	--	--	--	--

Plate I (continued)

Name	Altitude Indicator (Chronoscope)	Operating Range (ft.)	Weight (lbs.)	Max. Alt. (ft) Unit Wt. (lb)	Remarks: Accuracy, Price, Etc.
Behm (BEHMLOT)	Electro-mechanical oscilloscope.	5-300	34	9	Installed and used on several dirigibles. Tested on several airplanes. Error about $\pm 5$ ft. on landing and $\pm 12$ ft. at upper limit of range in adverse weather. Available commercially from Behm Beholot - Fabrik, Kiel. Price RM. 4,600.
Wandillon	Incandescent light and shutter rotating at constant speed along circular scale. Intermittent readings.	--	--	--	Secret investigation.
Rice (General Electric)	Constant speed chronoscope using method of auditory- visual coincidence.	First 5-800 cruising type: 5-1400 gliding Later 5-1800 cruising type:	First 45 type: no compressor Later 25 type: no compressor	18 31 48	Installed on American dirigibles. Tested by U. S. Army Air Corps. Blending of outgoing signal with echo at altitude of approximately 5 ft. used in landing.
Florissen (SOAM)	Constant speed chronoscope using method of auditory- visual coincidence. (Experimental: Direct reading oscillograph)	20-500 cruising 20-900 throttled	First 45 type: incl. air comp. 12 Later 31 type: incl. air comp. 12	11 20 16 29	Trained observer can hold error within 10 ft. Average error 5%. Latest model available commercially from Societe de Condensation et d'Applications Mecaniques. Price 15,400 - 22,000 Francs francais.
Dubois Laboureur (CEMA)	Continuous direct reading electrical chronoscope.	16-820 cruising	50 Incl. air comp. 10.	15	Error of about $\pm 2$ ft. up to 75 ft., $\pm 3$ ft. from 75 ft. to 150 ft., and $\pm 30$ ft. max. at higher altitudes. Available commercially from Constructions Electro-Mecaniques d'Amièrès. Price 150 livres - Sterling.
Jaquet Budin	Direct reading electrical frequency meter. Contin- uous readings.	1-160	20	6	Accuracy of $\pm 1$ ft. at low altitude. Designed particularly for landings. Comparatively small in size.
Delsasso	Neon lamp rotating at con- stant speed along circular scale. Intermittent read- ings.	4-350	--	--	Experimental apparatus tested on Goodyear blimp.
Echoscope	Direct indicating electro- mechanical chronoscope. Intermittent readings.	1-300 1-1000	61 Incl. air tank 22 valve 6	15	Used on Hindenburg (LZ129). To be installed on LZ130. Error $\pm 1$ ft. Available commercially from Electroacoustic G.m.b.H., Kiel. RM 5,100. Delivery 6 months.
Henry Hughes and Son	--	10-800	--	--	Information based on newspaper article which described only ground tests. Still in experi- mental stage.

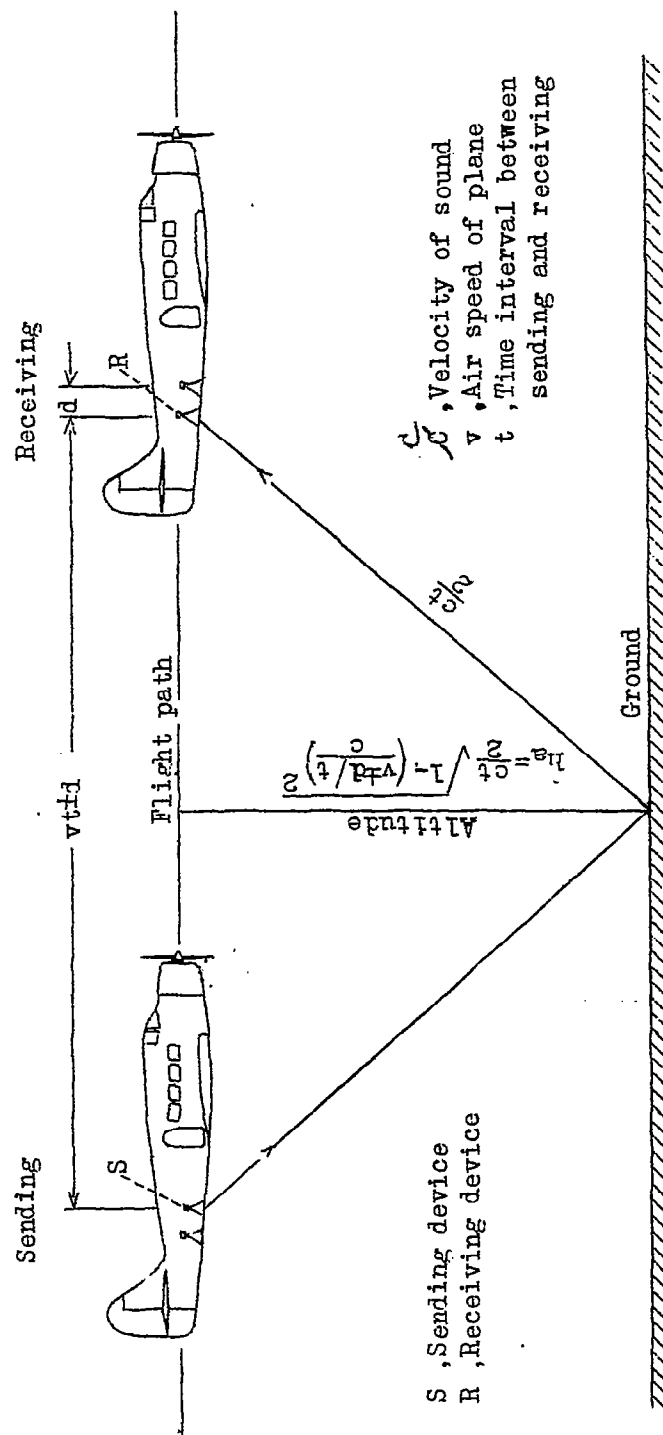


Figure 1.- Sonic method for measuring altitude.

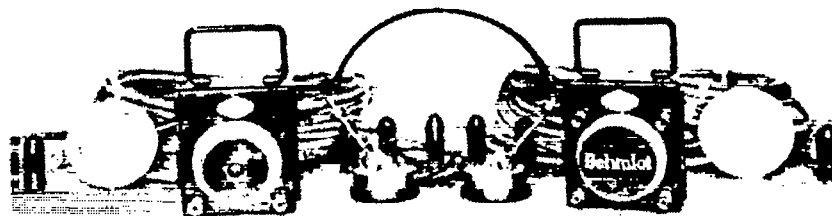


Figure 2.- Behmlot type IV A  
Ref. 5

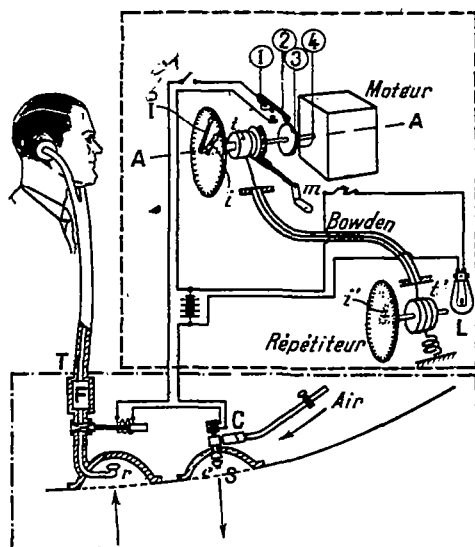


Figure 3.- Florisson-SCAM  
visual-acoustic  
coincidence altimeter. Ref. 18

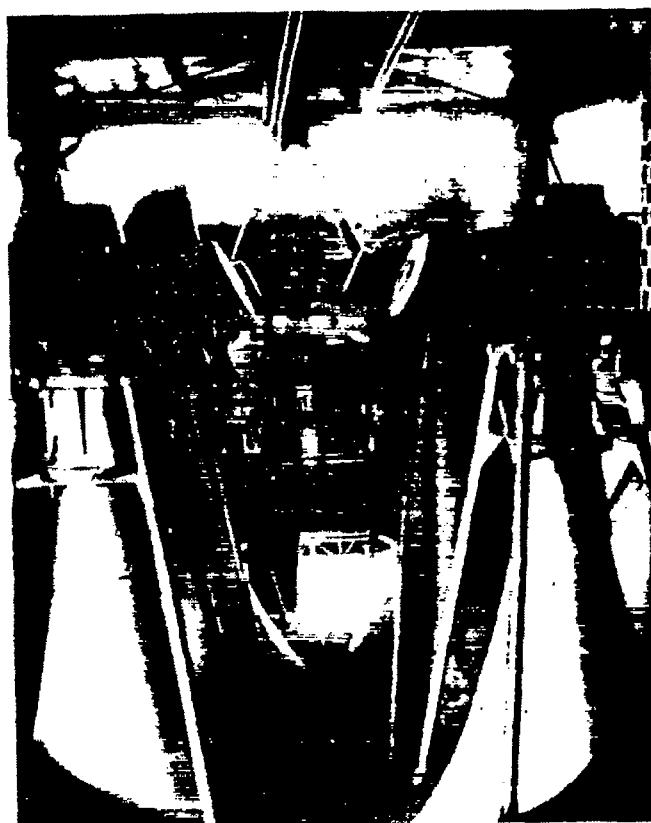


Figure 4.- Loudspeaker installation  
(Nandillon) Ref. 11

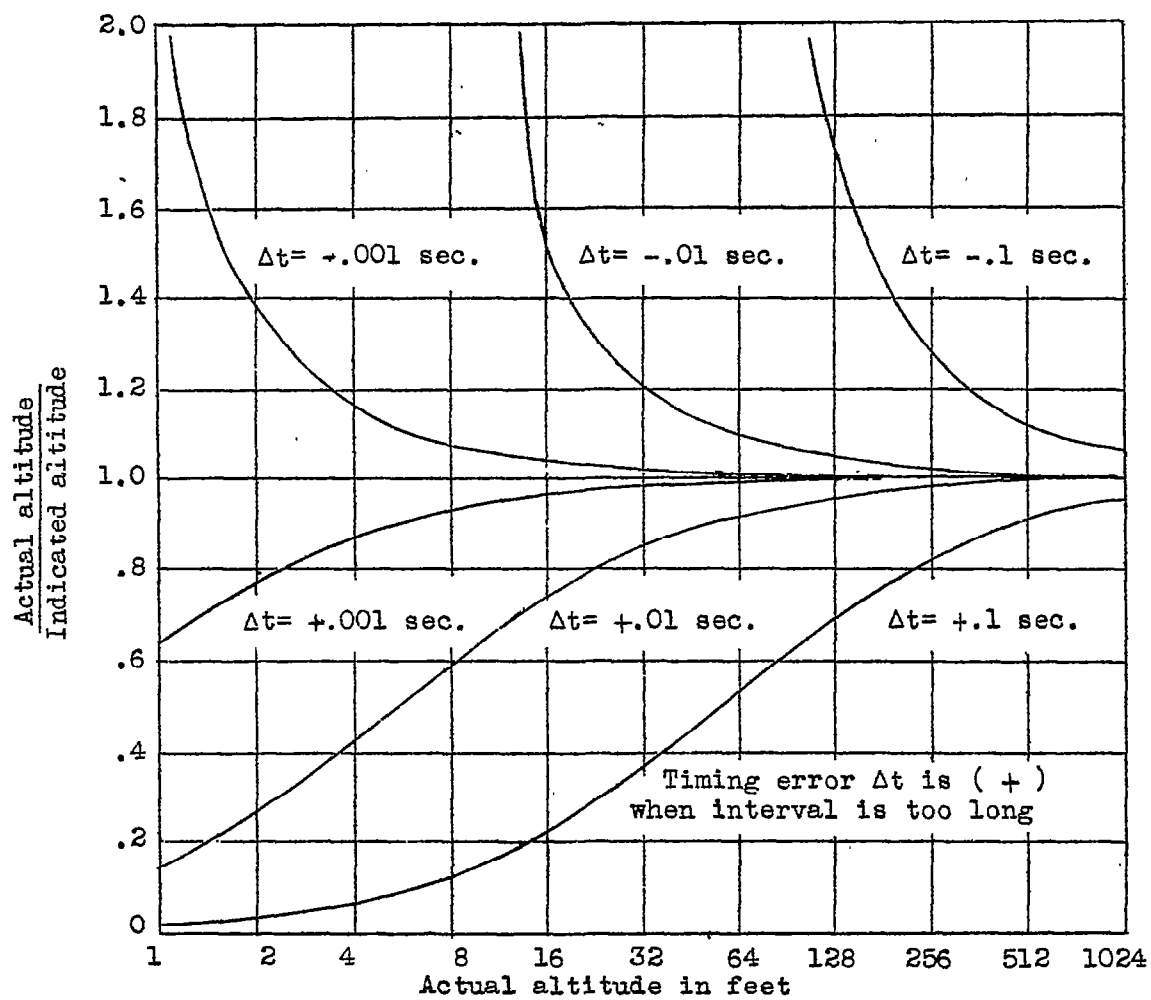


Figure 5.- Effect of timing errors  
when  $\frac{v \Delta t}{c_0} \ll 1$  and  $c_0 = 1085$  ft./sec.

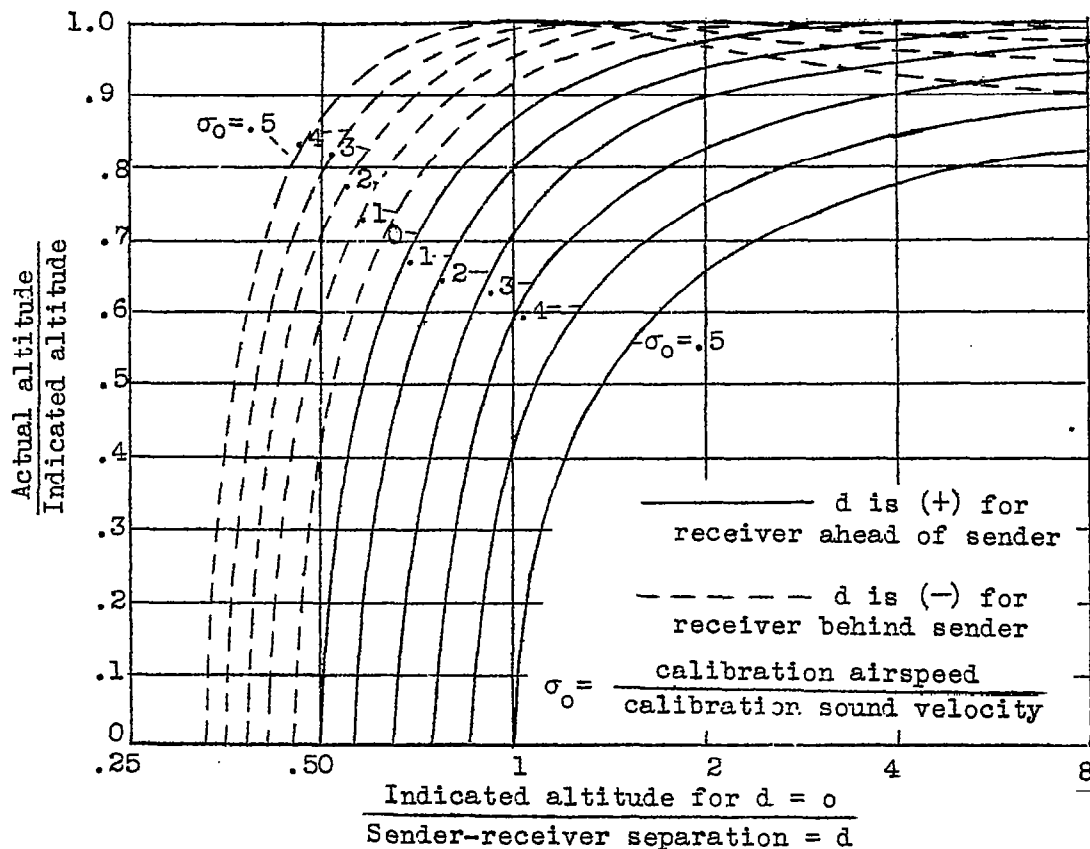


Figure 6.- Effect of sender-receiver separation for various airspeeds.

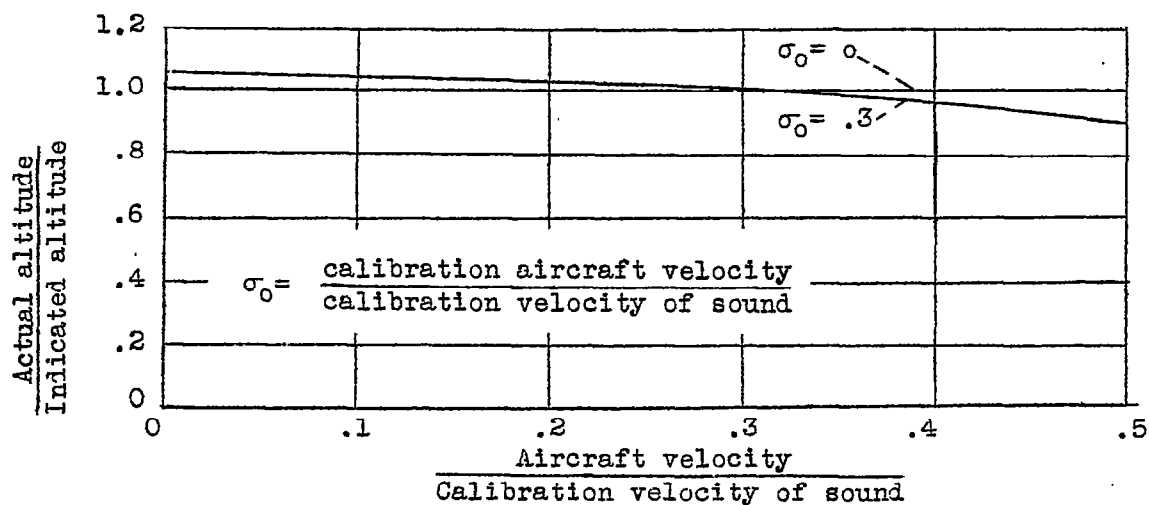
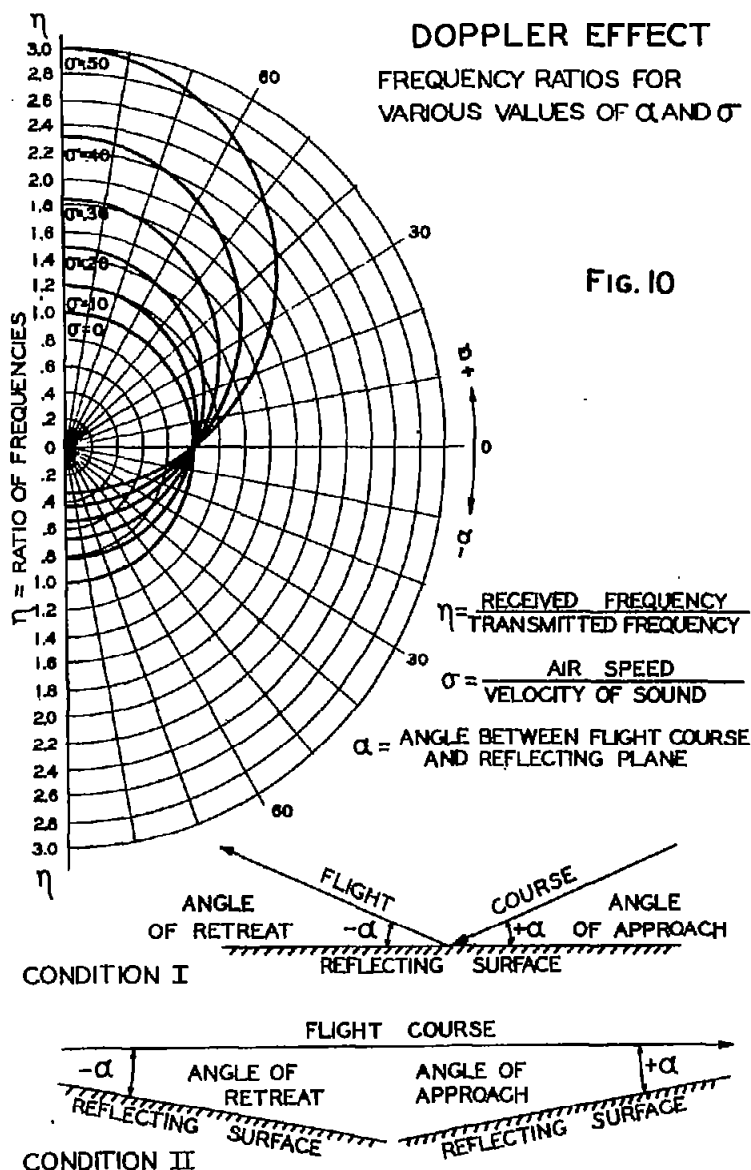
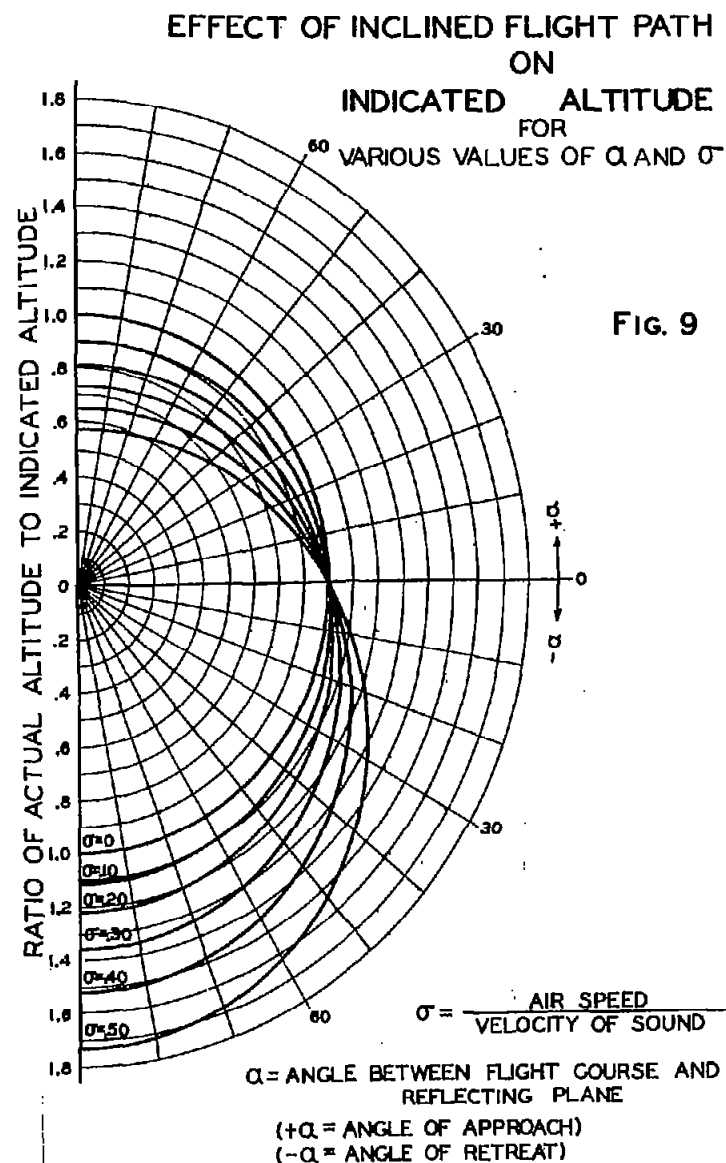


Figure 7.- Effect of aircraft velocity when  $d/t \ll v$ .





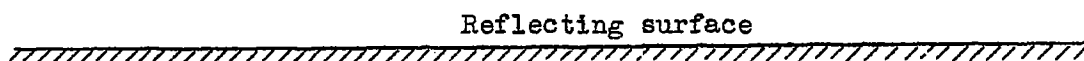
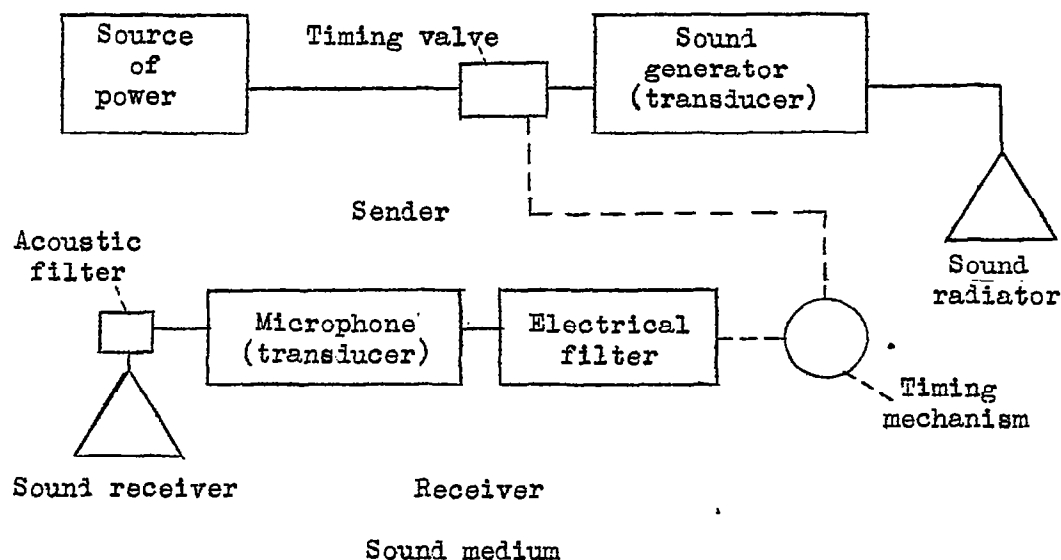
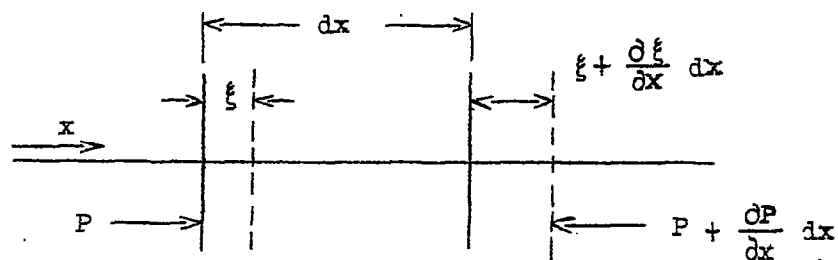


Figure 11.- Essential acoustic elements of a sonic altimeter.



$P$ , Pressure

$x$ , Distance measured normal to plane wave front

$\xi$ , Displacement of particles from equilibrium position

Figure 12.- Longitudinal displacements in a plane sound wave.

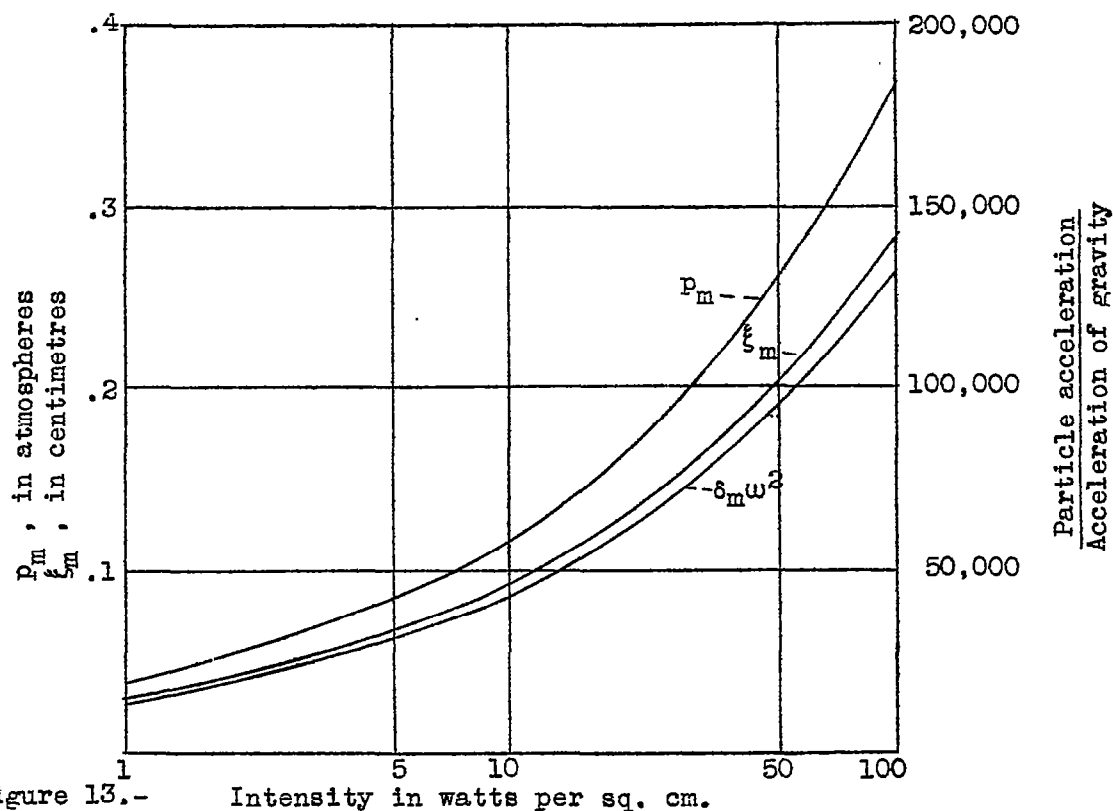


Figure 13.- Intensity in watts per sq. cm.

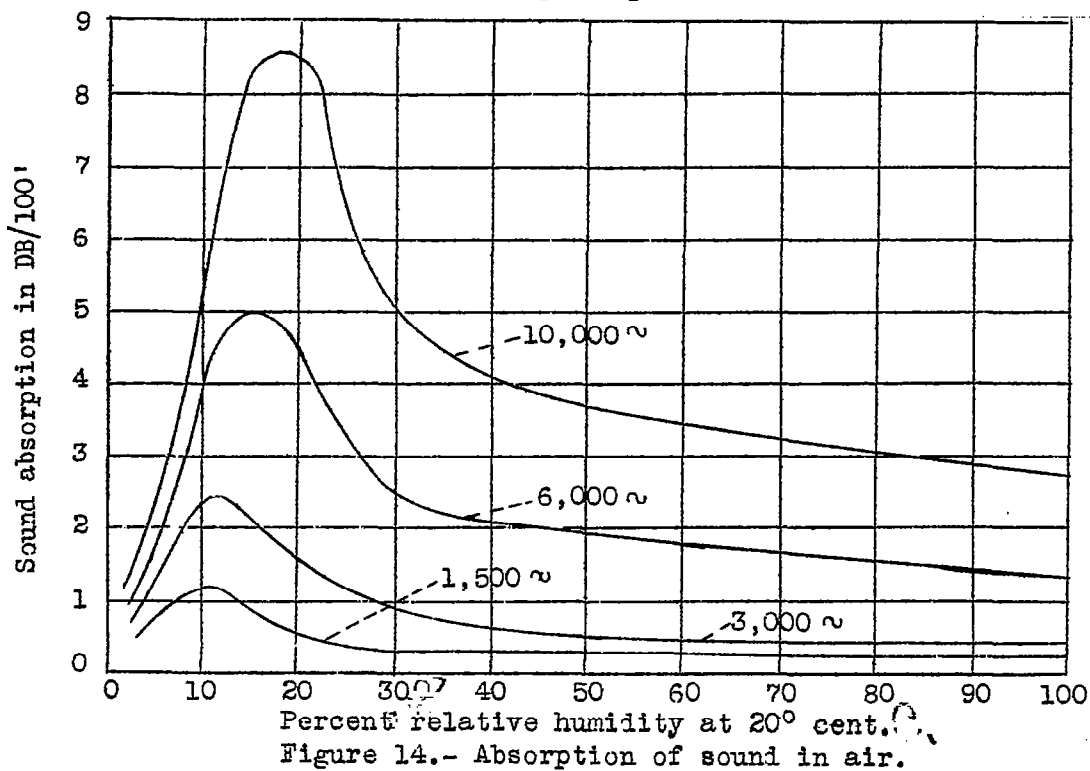


Figure 14.- Absorption of sound in air.

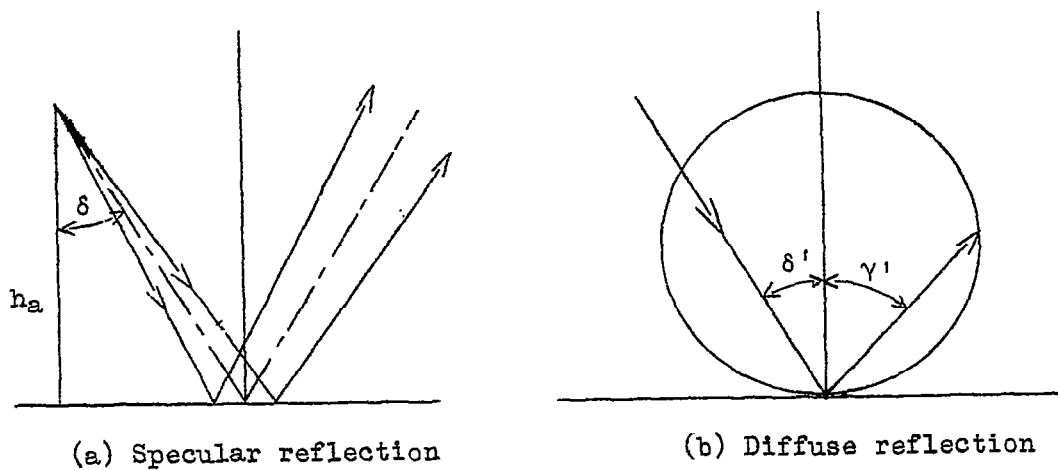


Figure 15.- Intensity distributions.

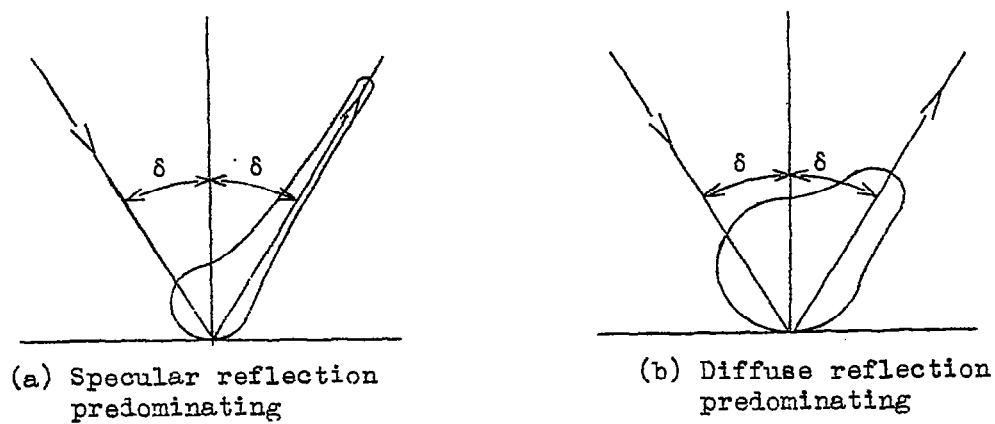


Figure 16.- Intensity distributions.

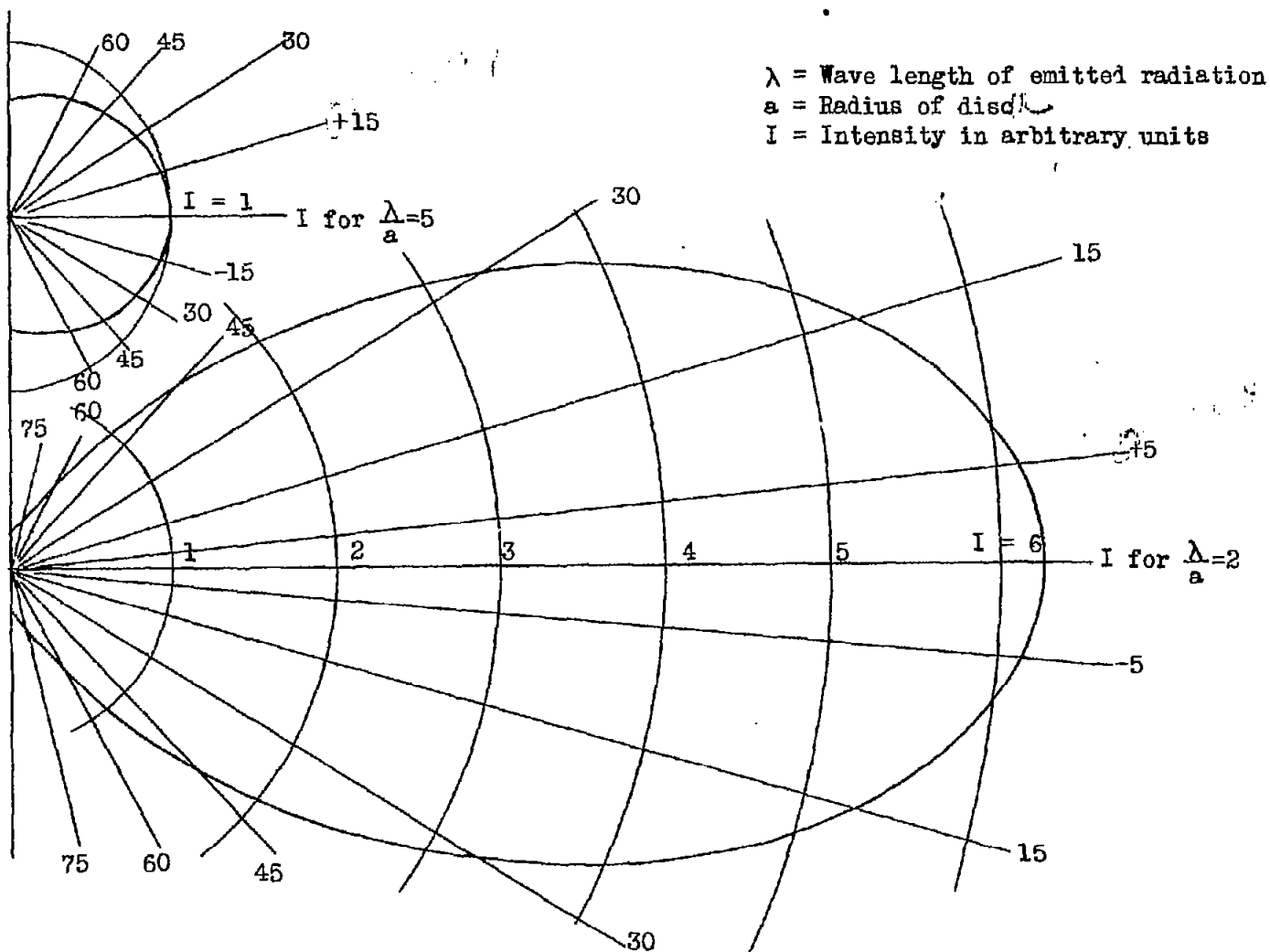


Figure 17.- Distribution of intensity of sound radiation from a disc for two frequencies.

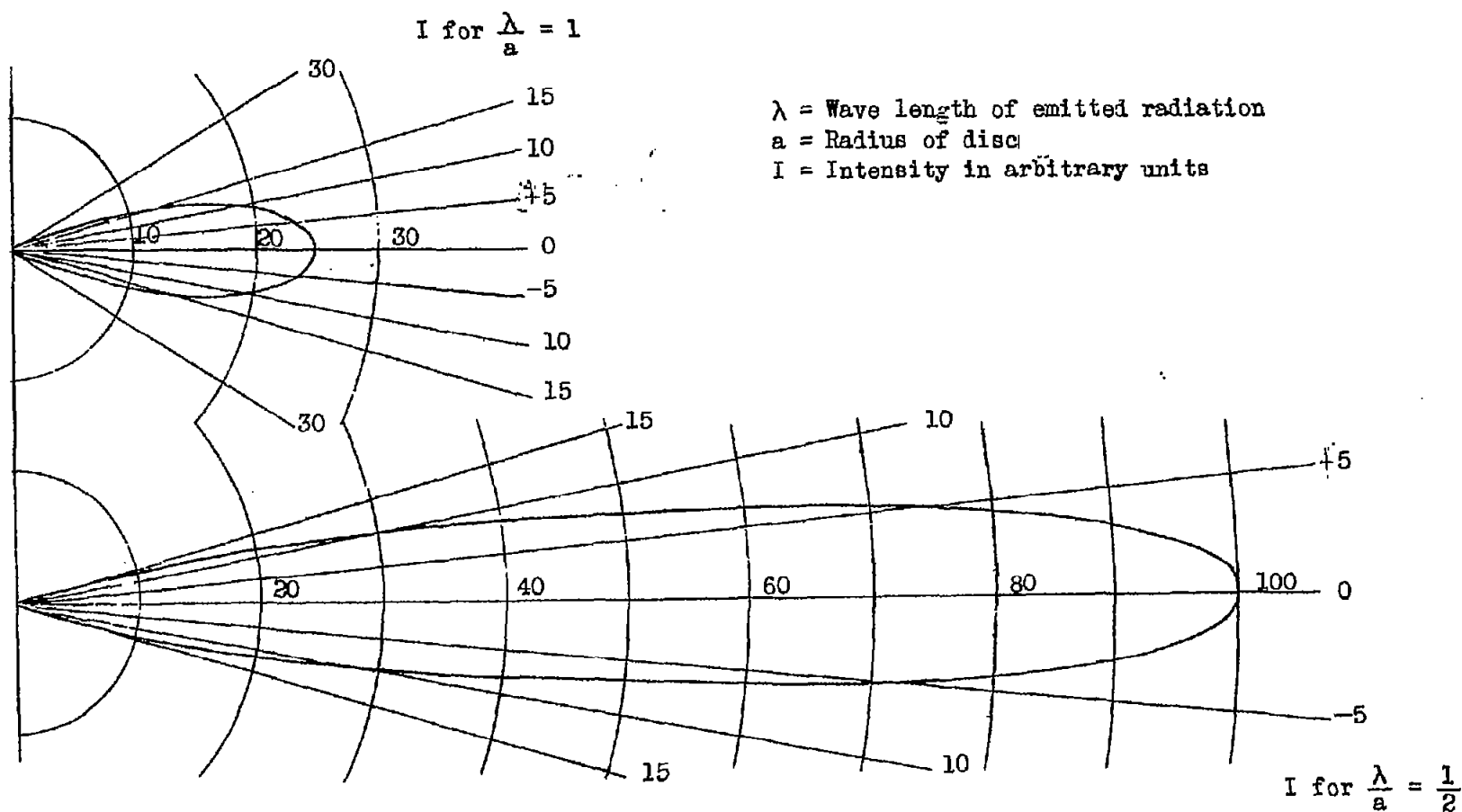


Figure 18.- Distribution of intensity of sound radiation from a disc for two frequencies.

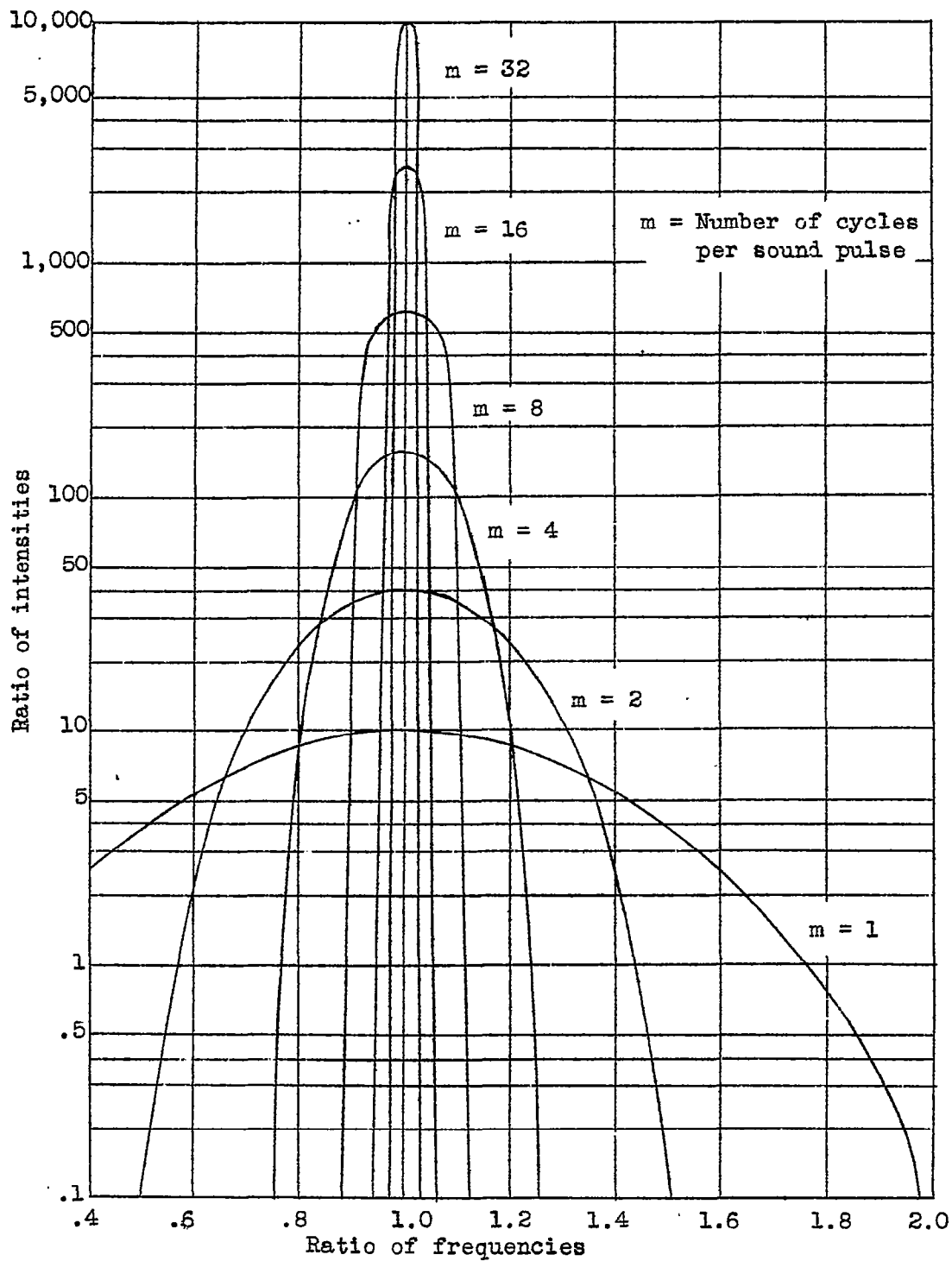
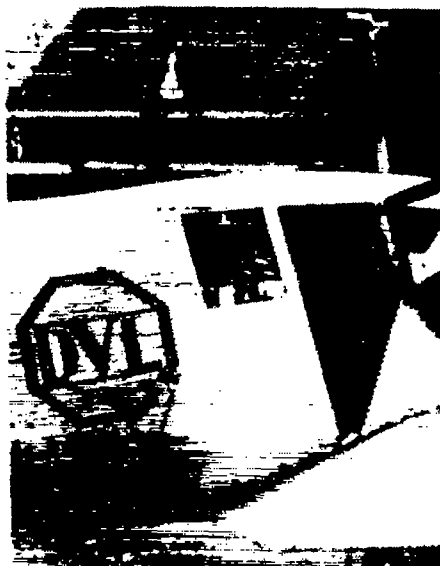


Figure 19.- Intensity-frequency-pulse length chart.



Behm  
Luftlot

Figure 20.-  
Pistol  
sender.  
Ref. 12



Figure 21.-  
Carbon  
microphone  
receiver.  
Ref. 12

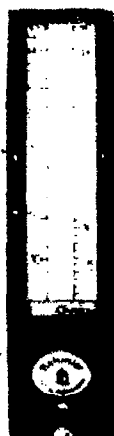


Figure 22.-  
Altitude  
indicator.  
Ref. 12

Figure 24.-  
Altimeter  
circuit.  
Ref. 4

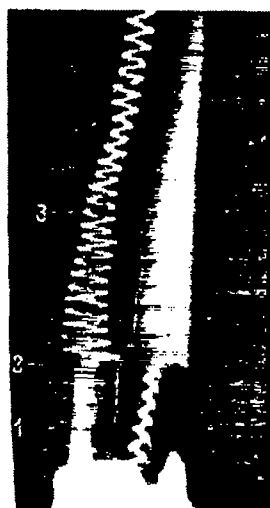
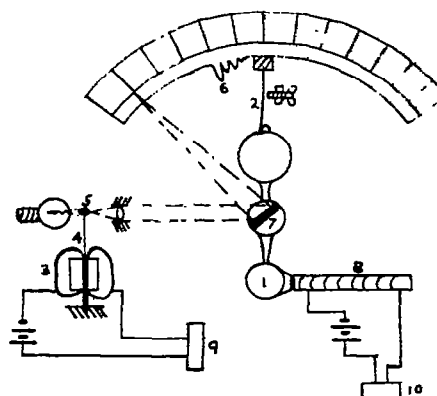


Figure 23.-  
Oscillograph  
trace  
on  
altitude  
indicator.  
Ref. 12

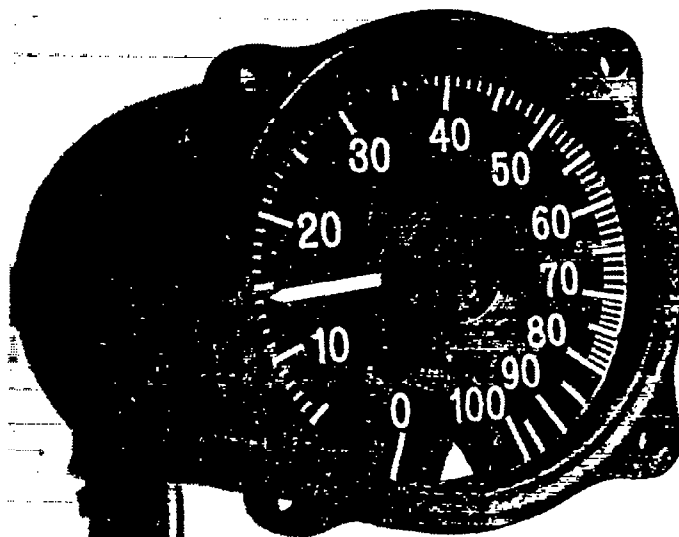


Figure 26.- Altitude indicator of Behm Type L XI (Natural size)

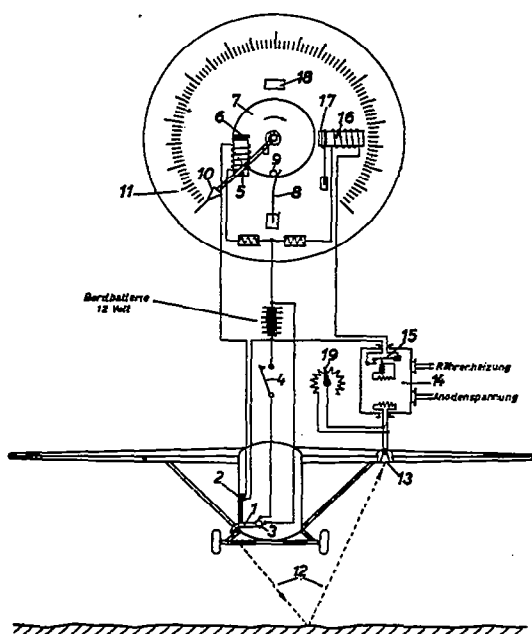


Figure 25.- Altimeter circuit of  
Behmlot Type LX I.  
Ref. 8

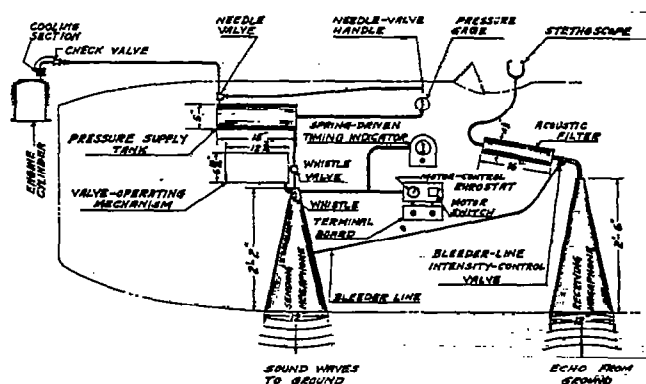


Figure 27.- Diagram of sonic altimeter installation.  
G.E. Co. Ref. 13

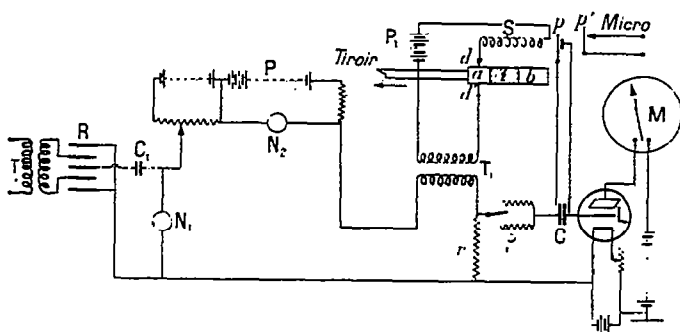


Figure 37.- Circuit of Laboureur-Dubois  
chronograph. Ref. 18

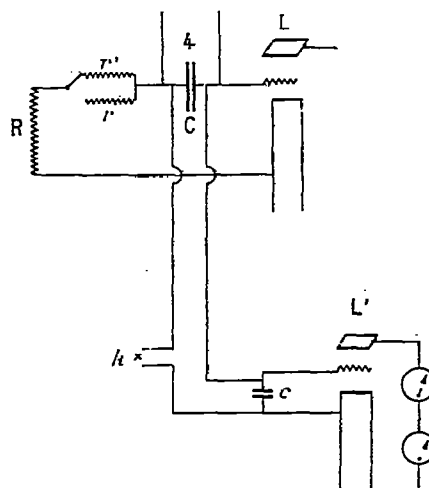


Figure 38.- Auxiliary circuit of  
Laboureur-Dubois contin-  
uous reading chronograph.

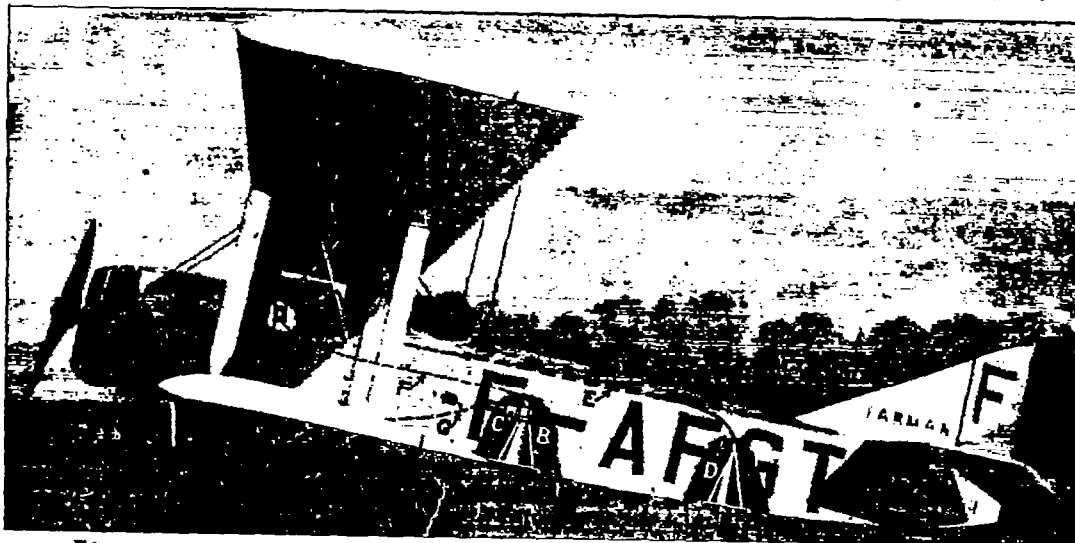


Figure 34.- Installation of Florisson-SCAM altimeter. Ref. 17



Figure 29.- Transmitting equipment G.E. Co. sonic altimeter. Ref. 13

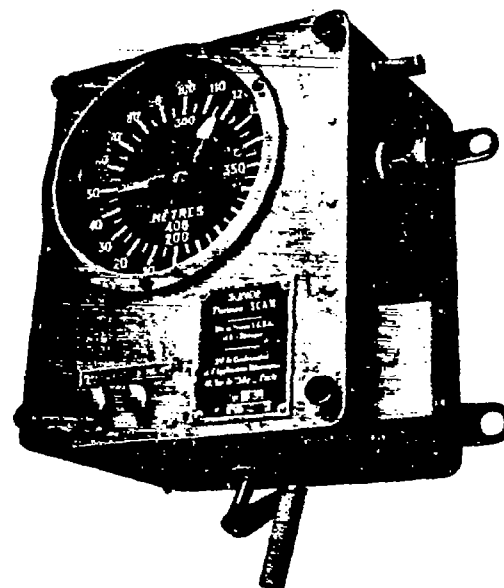


Figure 33.- Florisson-SCAM chronograph.

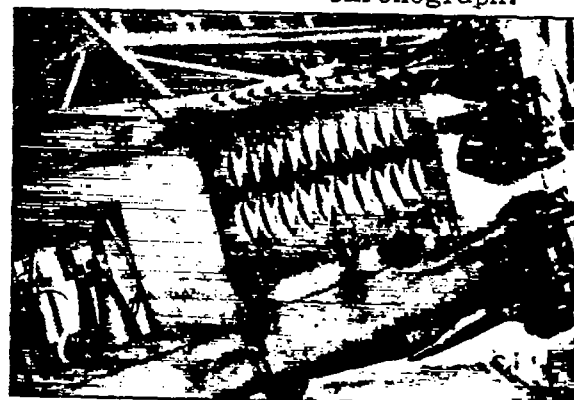
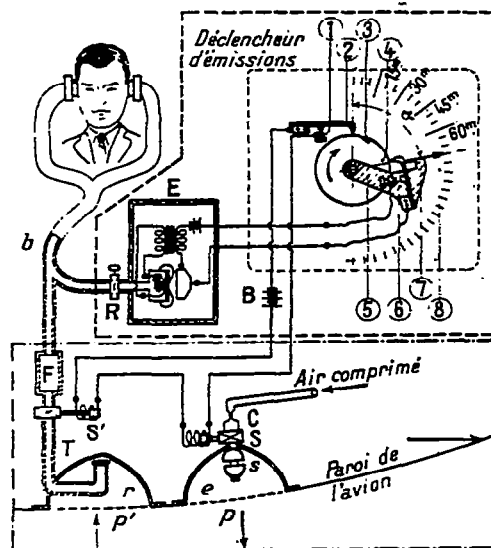
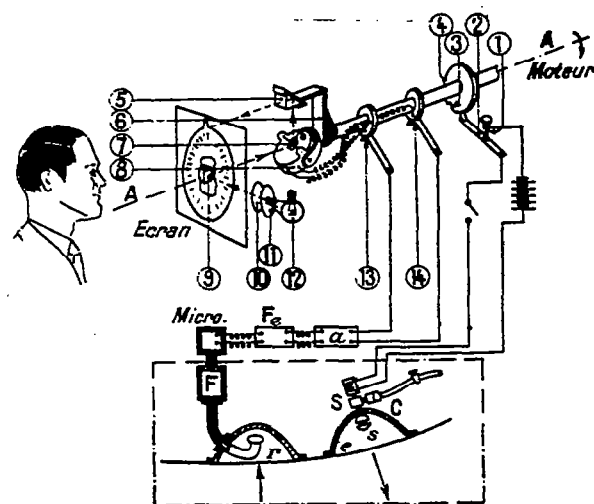


Figure 28.- Installation on airplane G.E. Co. sonic altimeter.



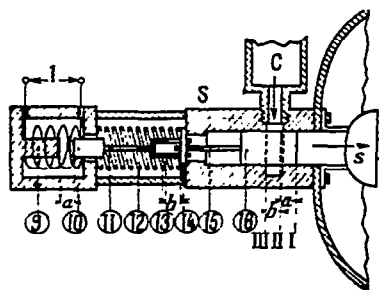
Florisson-SCAM Acoustic Coincidence Altimeter

Fig. 30



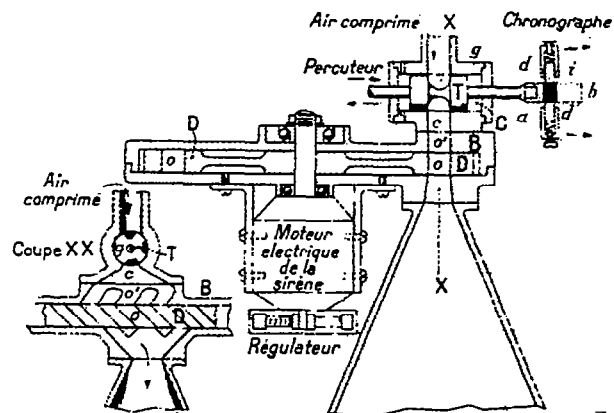
Florisson-SCAM Visual-Acoustic Coincidence Altimeter

Fig. 32



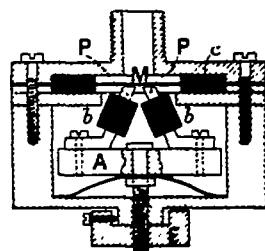
Quick Action Valve

Fig. 31



Details of Dubois-Laboureur Siren

Fig. 35



Dubois-Laboureur Microphone

Fig. 36

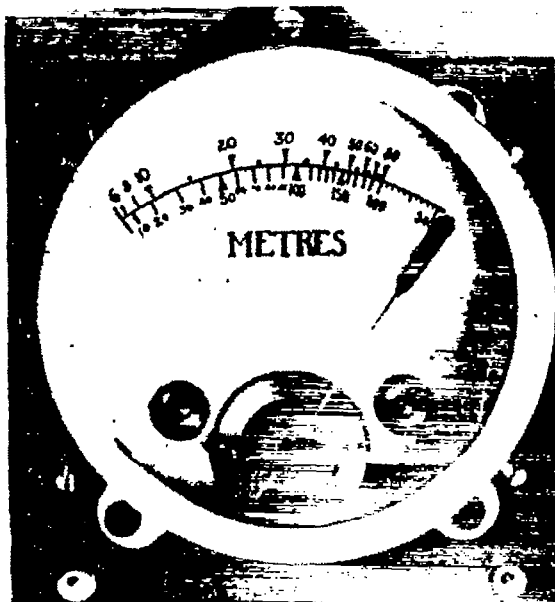


Figure 39.- CEMA altitude indicator(earlier type). Ref. 20



Figure 42.- CEMA altitude indicator(December 1936). Ref. A.C.

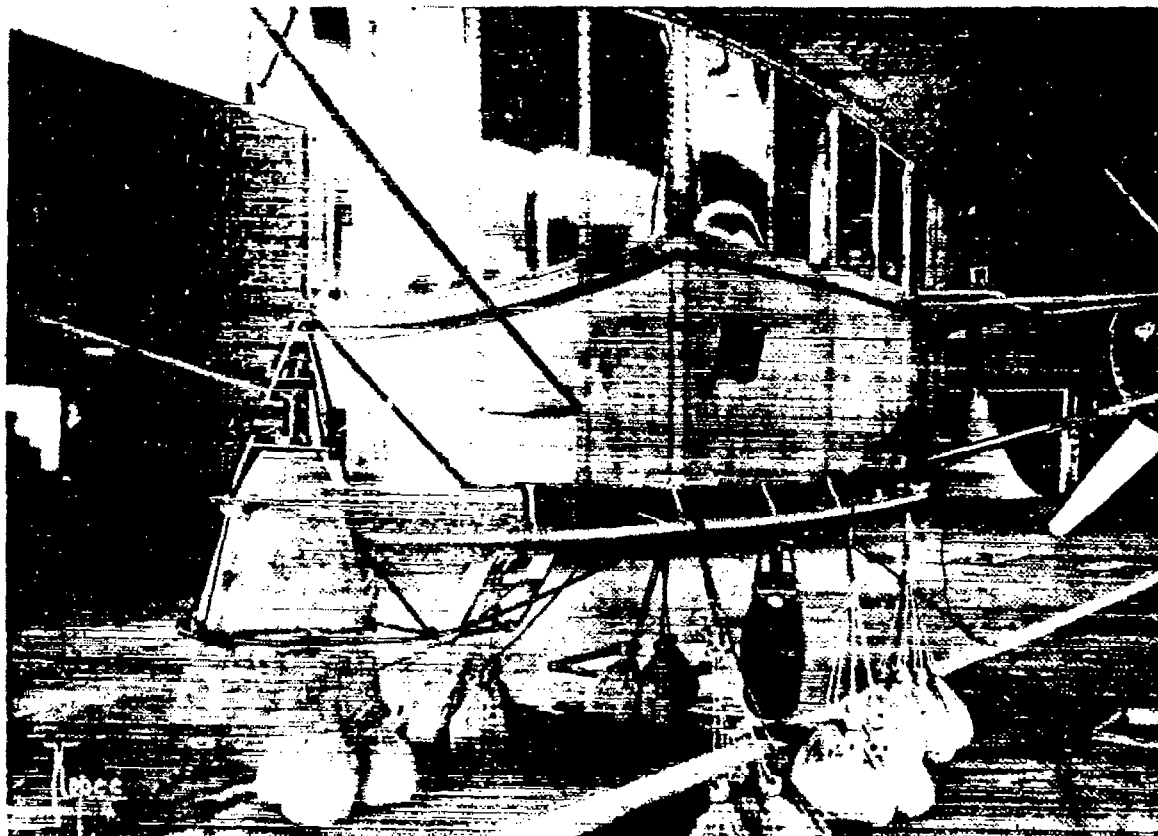
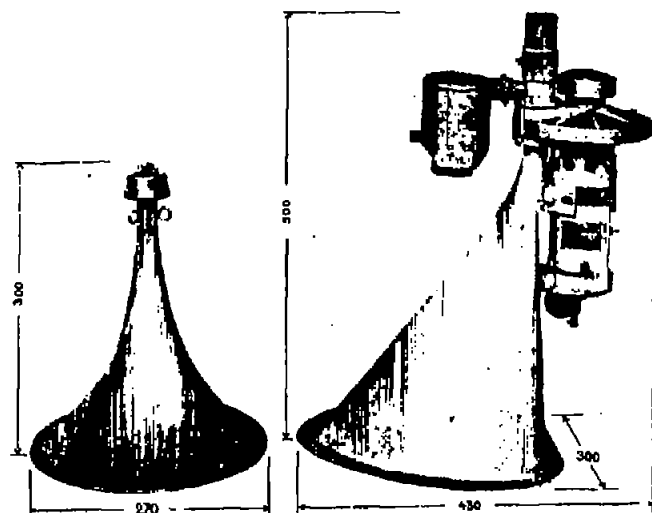


Figure 53.-Delsasso altimeter installation on blimp. Ref. 26



Microphone

Siren

Figure 40.- Dubois-Laboureur sender and receiver(December 1936)

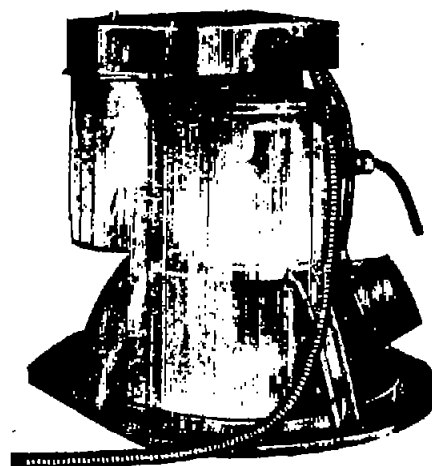


Figure 55.- Echoscope siren, Ref. 28

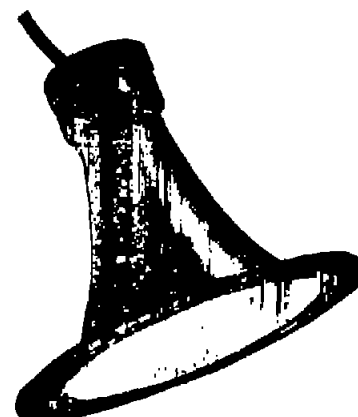


Figure 56.- Echoscope receiver.

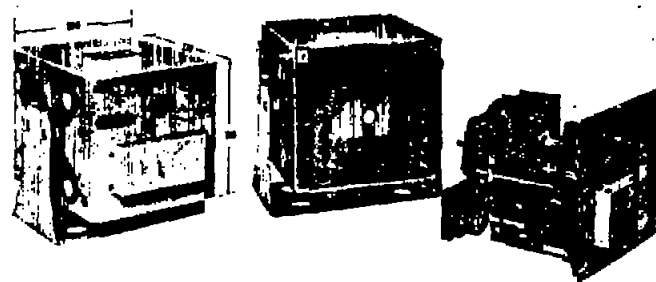


Figure 41.- Dubois-Laboureur amplifier-filter and chronograph unit. (December 1936) Ref. A.O.

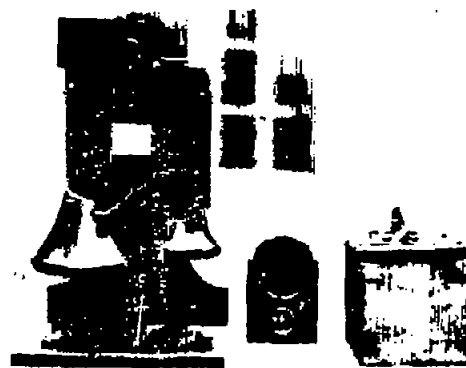


Figure 47.- Elements of Jacquet-Badin altimeter.

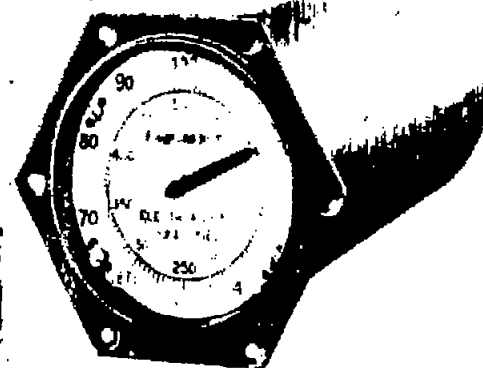
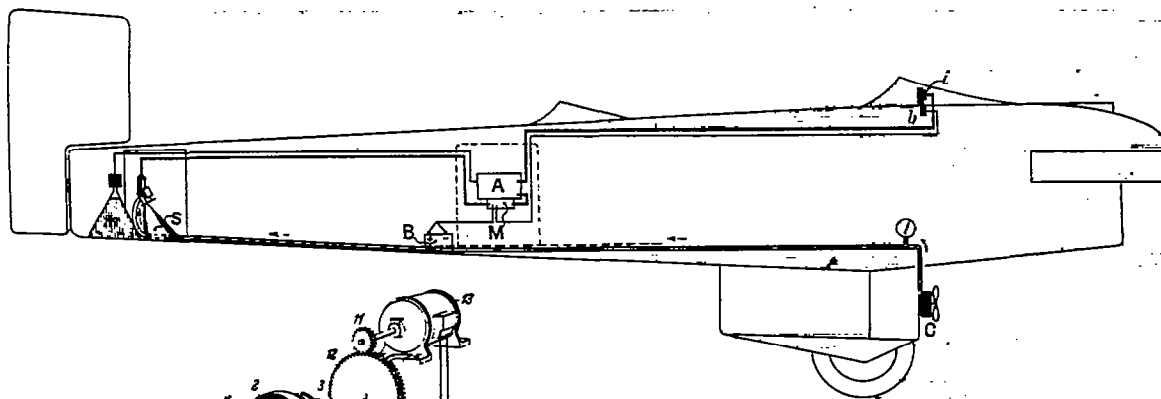


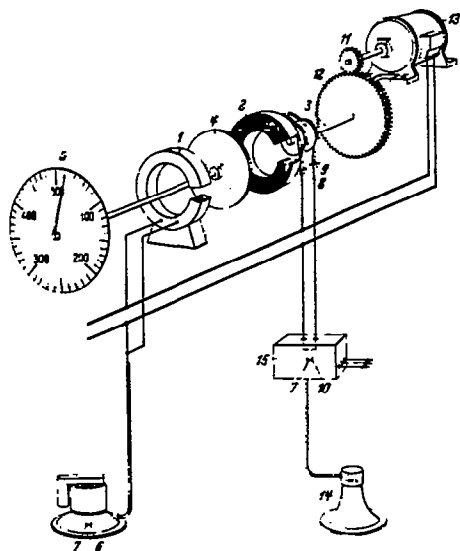
Figure 58.- Echoscope indicator.



Schematic Installation of  
Dubois-Laboureur Altimeter

Fig. 43

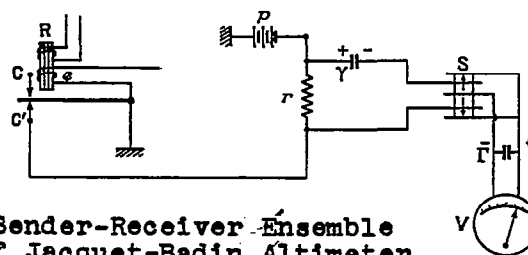
Ref. 20



Echoscope Circuit

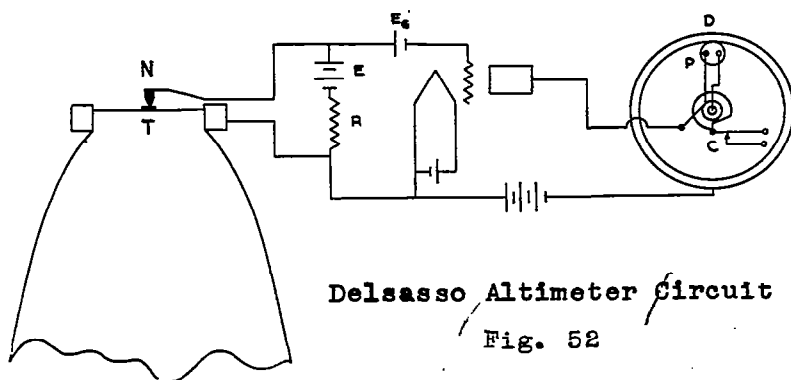
Fig. 57

Ref. 28



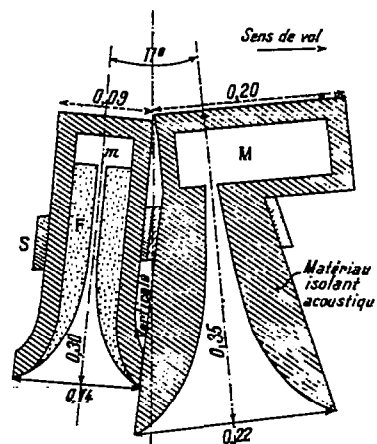
Sender-Receiver Ensemble  
of Jacquet-Badin Altimeter

Fig. 49 Ref. 25



Delsasso Altimeter Circuit

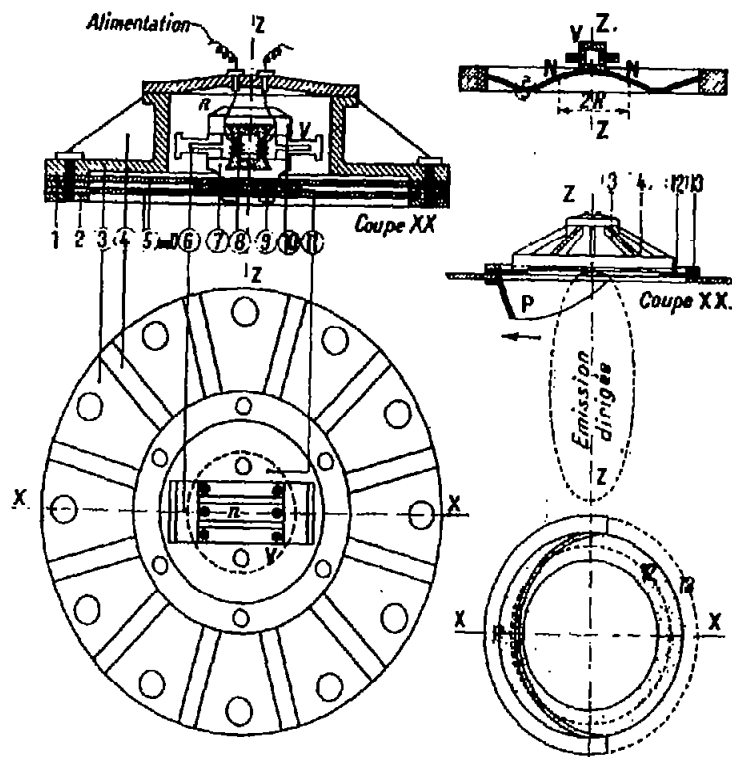
Fig. 52



Jacquet - Badin  
Frequency Meter Circuit

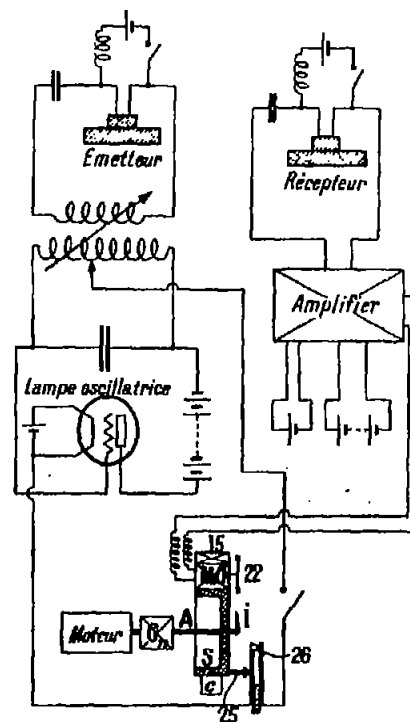
Fig. 48

Ref. 18



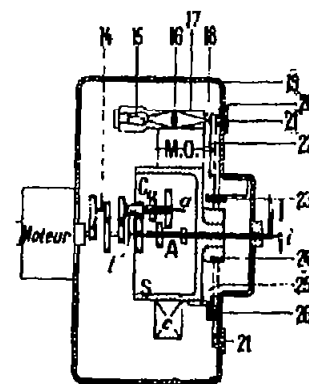
Nandillon's Directional Diaphragm.

Fig. 44



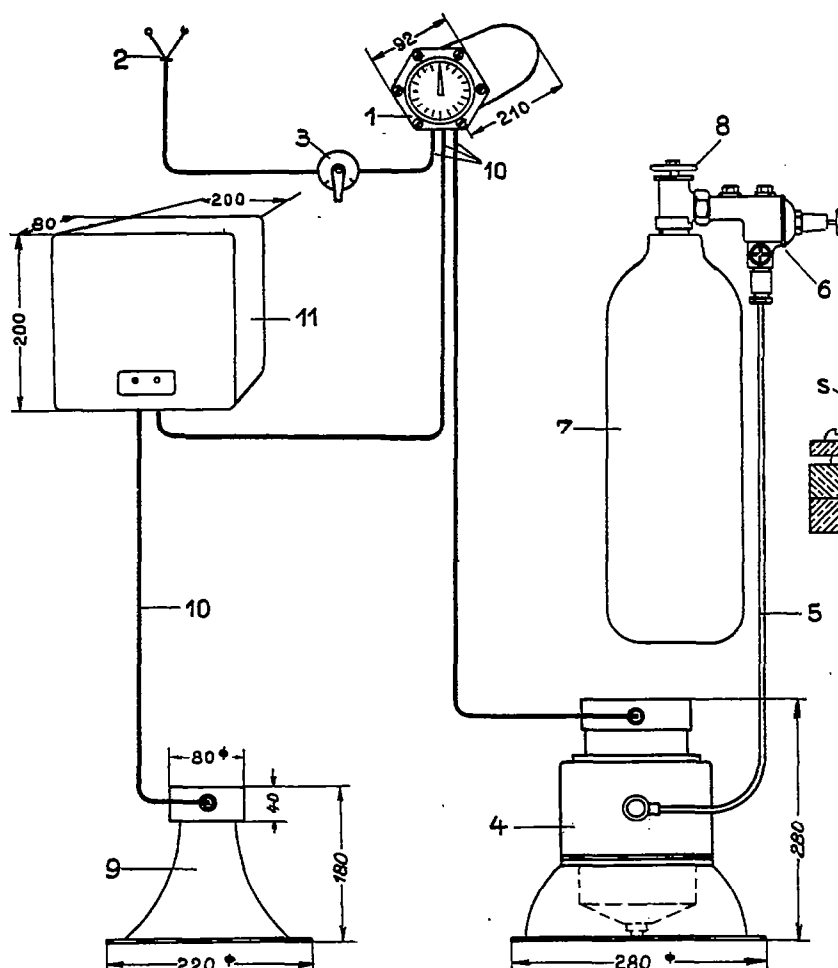
Altimeter Circuit

Fig. 45



Altitude Indicator

Fig. 46



	Denomination	Weight in kilos	
1	indicating device	2.2	
2	connection to the battery	—	
3	switch	0.2	
4	siren	8.5	
5	copper tube	—	
6	reduction valve	1.0	
7	compressed air bottle		13.0
8	main valve		
9	receiver	0.8	
10	cable	—	
11	amplifier	2.1	
	total	14.8	13.0

Figure 54.- Installation diagram of Echoscope. Ref. 28

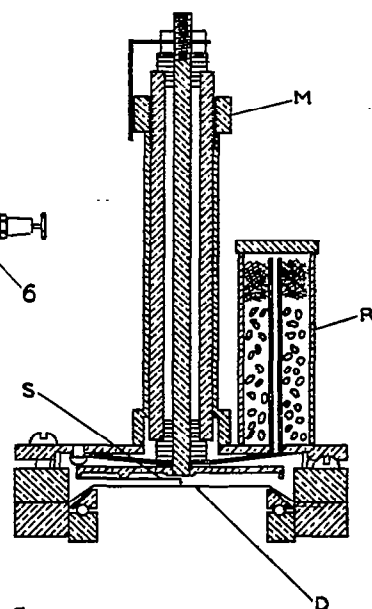


Figure 51.- Delsasso receiver, Ref. 26

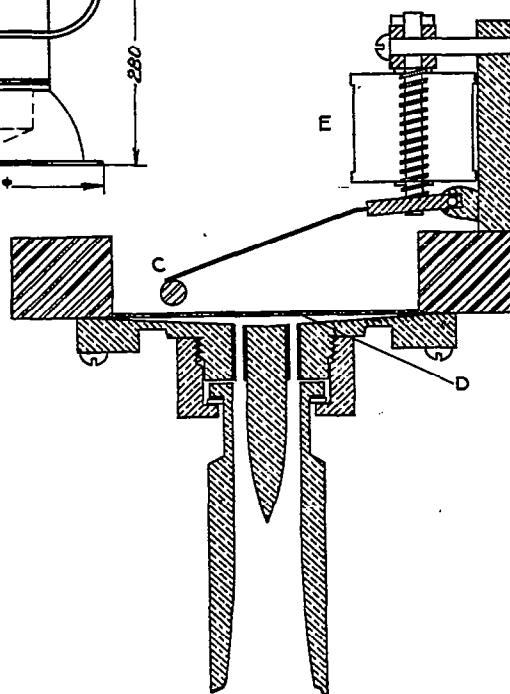


Figure 50.- Delsasso sender.